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Correction Procedures for Aircraft Noise Data
Volume 5: Propeller Aircraft Noise

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16. Abstract

This report examines three particular problem areas associated with the measurement of noise levels of propeller-driven small airplanes required to comply with FAR Part 36, Appendix F. These problems are directly related to effects of atmospheric conditions on (1) the performance capabilities of an airplane when tested at various barometric pressures and altitude densities; (2) the noise signature generated at such conditions; and (3) the propagation of sound from the airplane to the measuring station. The first two of these have been addressed by deriving potential correction procedures which could be applied to noise levels obtained by tests not in strict compliance with Appendix F. These corrections are based on aircraft operations conducted within a specific margin of power setting. The corresponding measured noise levels are subsequently corrected for variation of propeller tip speed, forward velocity and barometric pressure relative to predetermined reference conditions. The third effect, that of sound propagation, is examined by applying SAE ARP 866A to a typical propeller airplane noise spectrum and demonstrating the range of A-weighted noise levels that would result within a range of ambient conditions.

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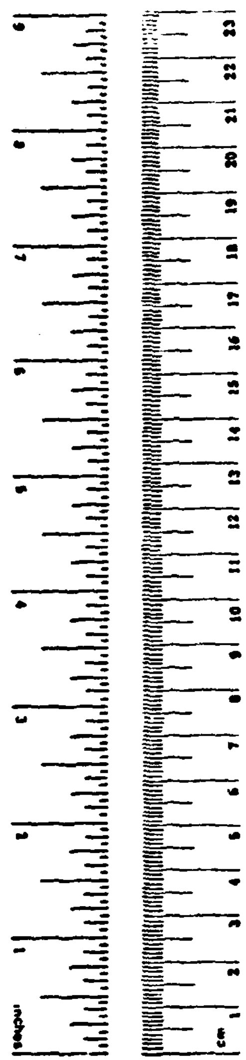
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

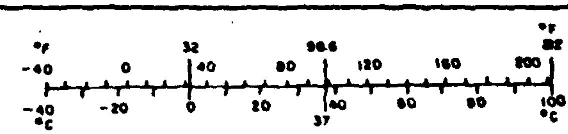
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

Federal Aviation Regulation Part 36, Appendix F,[1] reproduced as Appendix I of this report, defines procedures for the measurement and correction of noise levels for certification of propeller-driven small airplanes. These procedures are less complex than those required for larger aircraft, in that they require a corrected A-weighted sound level to be obtained for level flight conditions at a height of 1000 ft ±30 ft over a single measuring station. The corrected sound level is an average of maximum levels obtained from six valid test flights, with corrections for takeoff performance characteristics and as necessary atmospheric effects on sound propagation.

The purpose of the present study is to examine two of the constraints on test validity imposed by Appendix F. First, each test is required to be performed with the airplane ". . . (1) at not less than the highest power in the normal operating range provided in the Airplane Flight manual, or in any combination of approved manual material, approved placards or approved instrument markings; and (2) at stabilized speed with propellers synchronized and with the aircraft in cruise configuration, except that if the speed at the power setting prescribed in this paragraph would exceed the maximum speed authorized in level flight, accelerated flight is acceptable."

While this requirement generally imposes no significant difficulty in certification tests performed at airfields which are close to sea level altitude, there may be a very significant difficulty in performing valid tests at other airfields. For example, it may be required to perform certificqtion tests because of an acoustical change to an airplane, the nearest airfield being at an air density altitude of (say) 5000 to 6000 ft. The maximum achievable power setting may in such cases be limited, by altitude density, to much less than the maximum required by Appendix F. The problems to be addressed, therefore, are whether corrections can be developed for off-reference performance conditions and, if so, what correction procedure would give a sufficiently accurate estimate of the reference condition noise level.

The second constraint, concerning the allowable range of ambient conditions (the "ambient window") for valid tests, is in part,

- that the relative humidity is not higher than 90% or lower than 30%, and

- that the ambient temperature is not higher than 86°F (30°C) or lower than 41°F (5°C) at 33 feet above ground.

Where the test conditions are outside the range 68°F ±9°F (20°C ±5°C) or the humidity is lower than 40%, then corrections to account for atmospheric effects on sound propagation are necessary. These are referred to a reference ambient condition of 77°F, 25°C, 70% relative humidity.

The method to be used for such corrections is not specifically defined in Appendix F. It is required, however, that it be approved by FAA. An available method is that contained in SAE ARP 866A, referred to later in this report. This would require an octave or one-third octave band frequency spectrum to be obtained in order to correct the measured maximum A-weighted level for each test result. The changes in A-weighted level resulting from applying this correction are therefore examined in this report to determine whether a simplified method can be derived which would allow corrections to be applied directly to the measured A-weighted levels (i.e., without frequency spectrum analysis).

It is essential, of course, that any correction procedures developed for the above purposes should not detract from the main intent of FAR Part 36, which is to limit the noise of airplanes. The correction should not, therefore, give any benefit in noise level that would not have been obtained by testing at the reference conditions.

2.0 EFFECTS OF AIRPLANE PERFORMANCE ON NOISE LEVEL

2.1 Basic Considerations

The typical noise signature of propeller-driven airplanes, as illustrated in Figure 1, is dominated by the harmonic content at the propeller blade passage frequency and its multiples. The origins of these harmonics are only partly understood, the lower harmonics being associated with the steady loads (thrust and drag) rotating with the blades and imparting force fluctuations on the air at the propeller disk. The higher harmonics can be postulated as being generated by fluctuating (harmonic) blade loads, or other effects, the origins of which are still open to speculation. These are further discussed in Section 2.2 as they are the primary factors governing performance effects on the A-weighted sound level.

Engine and airframe noise components are generally regarded as being of little significance to the overflight noise level (at or near FAR Part 36 conditions). Exceptions would seem to be where the engine and drive system are considerably different from the norm, for example with a gear driven supercharged (twin-piston engined) system.[2]

Emphasis is therefore placed on determining the effects of propeller operating condition on the measured overflight sound level.

2.2 Propeller Noise

2.2.1 Overview

It is well-known that tip speed is the most dominant of the parameters which influence propeller noise. Thus, while differences in blade number, diameter, loading characteristics and tip thickness play a role in determining the "effective" forces which cause noise generation, relatively minor changes to the speed of rotation of these forces can far outweigh any of these other differences in terms of the eventual noise signature. Figure 2, derived from data presented in Reference 2 and augmented by data from other sources,[3, 4, 5] clearly shows this dependency for a wide range of different aircraft, all flown at or near the FAR Part 36 reference conditions. Figure 3 shows the same data corrected for differences in engine brake horsepower (BHP) by the factor of $-10 \log (BHP/200)$, as in Reference 2. In each of these illustrations the base parameter is the helical tip Mach Number, M_H, where

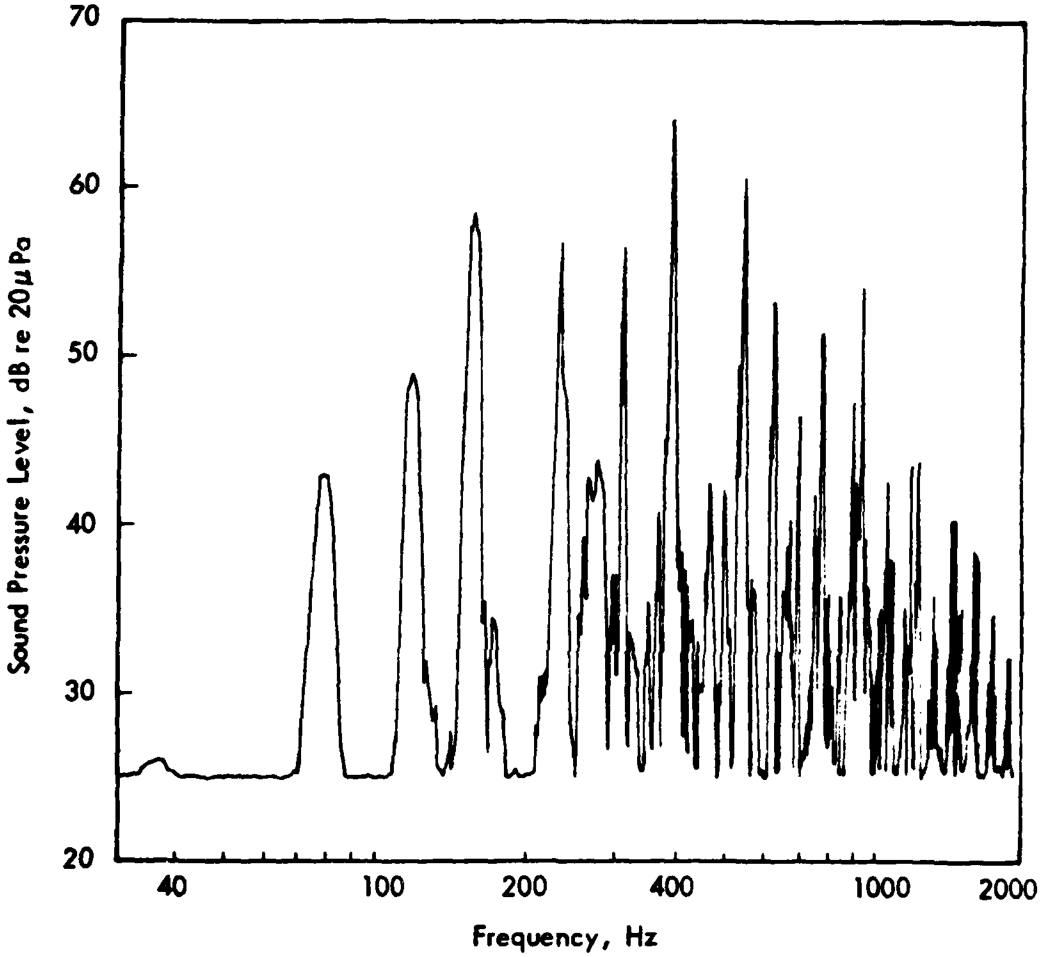

Figure 1. Propeller Aircraft Noise Signature (Ref. 2)

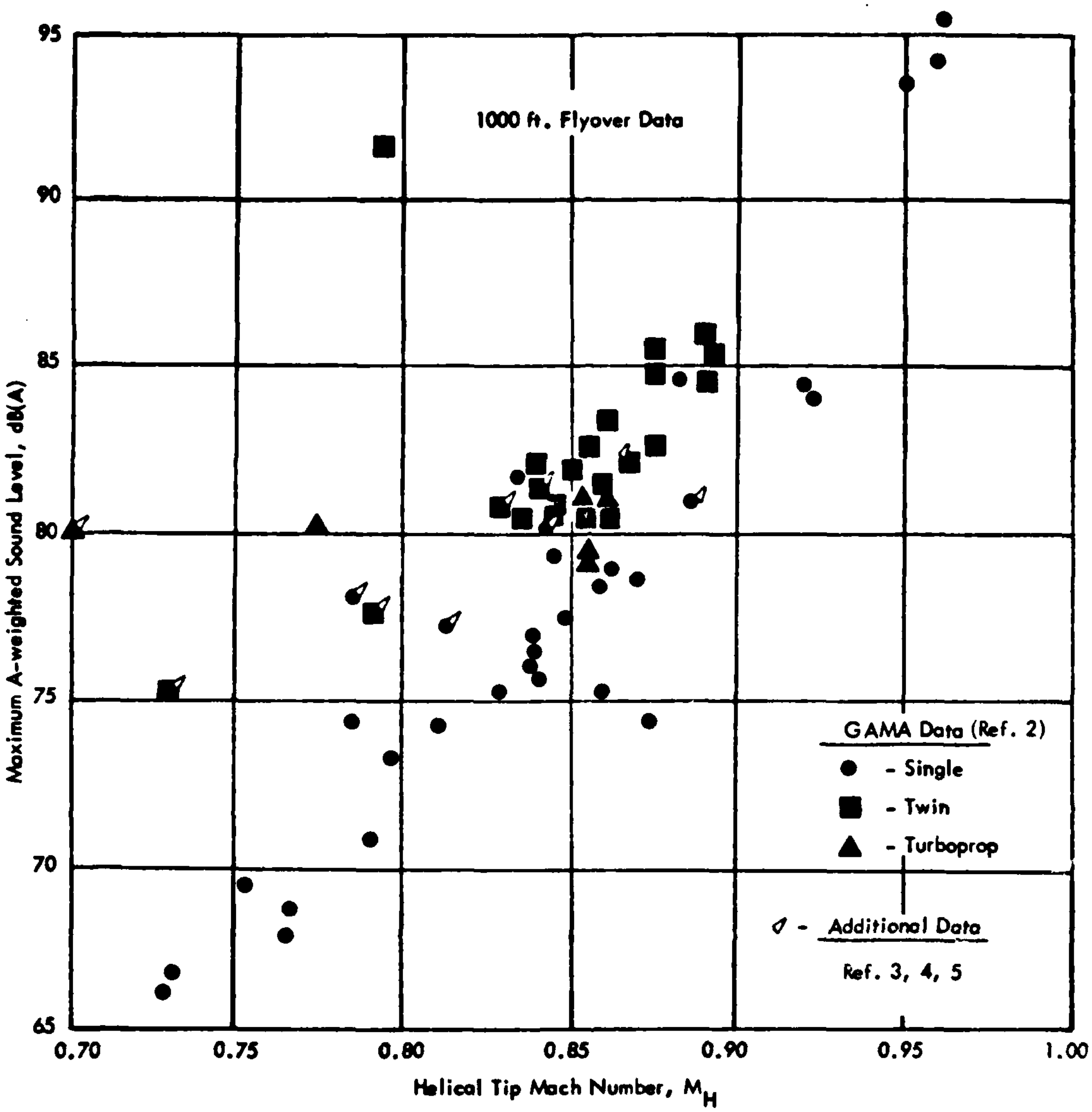

Figure 2. Propeller-Driven Airplane Noise Levels at FAR Part 36 Conditions (Data from References 2, 3, 4 and 5)

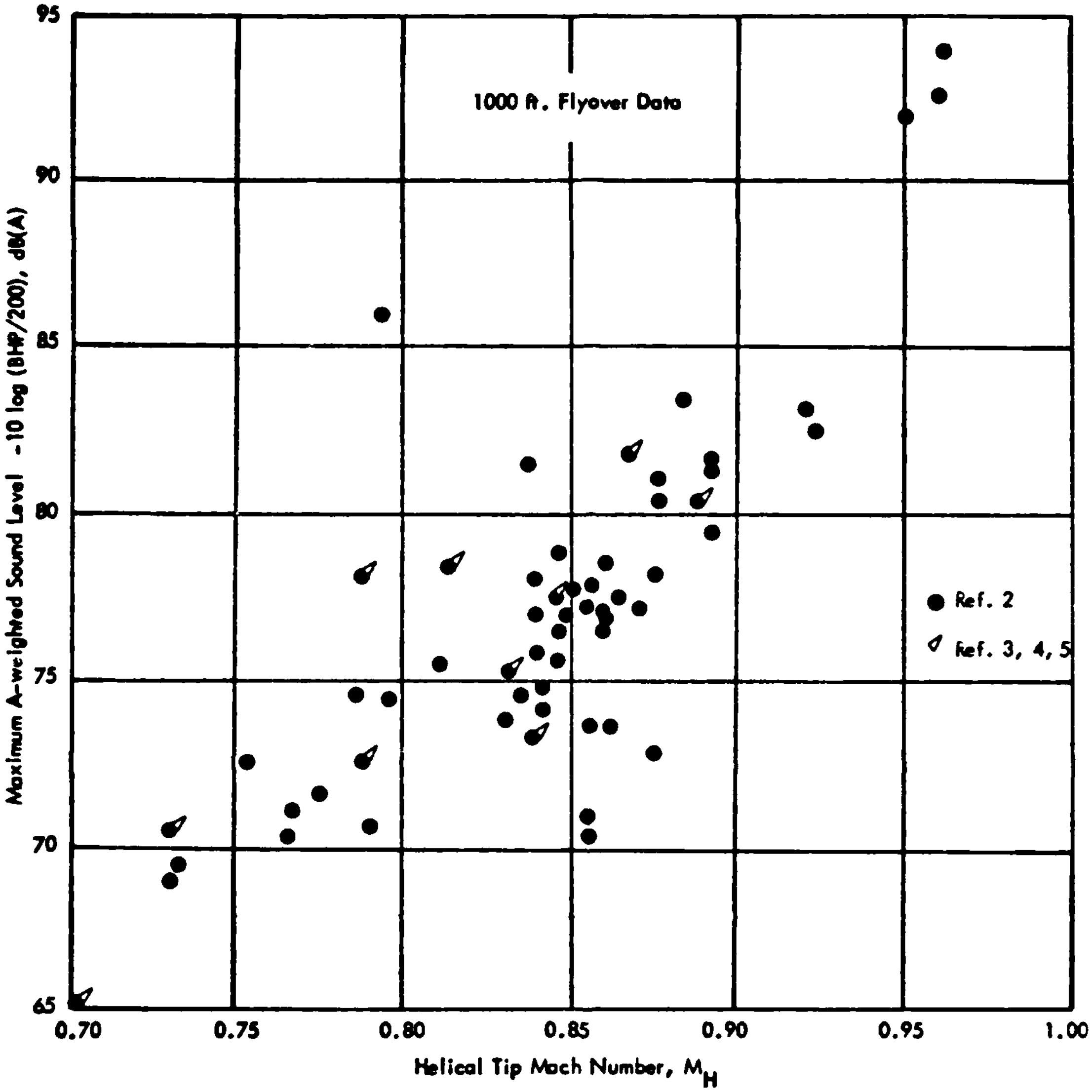

Figure 3. Propeller-Driven Airplane Noise Levels at FAR Part 36 Conditions (Data from References 2, 3, 4 and 5 normalized to 200 BHP by subtraction of 10 $\log_{10}$ BHP/200)

$$M_H = \frac{1}{c_o} (V_t{}^2 + V_x{}^2)^{1/2} \quad ,$$

c_o is the speed of sound, V_t is the propeller blade tip speed, and V_x is the airplane forward speed.

While giving an indication of the effects of M_H and BHP on the noise levels of different airplanes at the maximum power condition, the data do not show the effects of operating a specific airplane at other flight conditions. Measured (and authentic) noise data for the latter conditions are not readily available from normal test programs. The noise data used herein are therefore those measured in tests performed on a Cessna 172M and a Beechcraft B5-B33 in an FAA-sponsored study[5] of propeller noise as a function of engine power and test density altitude, supplemented by noise test results for various propellers applied to a light aircraft.[6] These data are presented in Tables 1 and 2, and Figure 4, respectively.

The first of these studies[5] provides noise data for two aircraft operating over a range of performance conditions (RPM, M_H, and percent maximum continuous power (MCP)) at three different airfields. The respective airfields are at different elevations - Ventura at 41 ft., Fox at 2350 ft., and Big Bear at 6750 ft. (The effect of airfield elevation is examined in Section 2.2.6 of this report.) The findings with regard to variation of performance conditions, as given in the study, were as follows:

The A-weighted sound level of the Cessna 172M varied as

$$L_A \propto 195 \log_{10} (M_H \text{ ratio}) \qquad , \text{dB(A)}$$

with an additional 0.1 dB(A) to be added for each 1 percent of MCP (maximum continuous power) below 100 percent MCP, to correct the noise level to 100 percent MCP.

For the Beechcraft B5-B33 (variable pitch propeller), the study findings were that

$$L_A \propto 240 \log_{10} (M_H \text{ ratio}) \qquad , \text{dB(A)}$$

with no additional correction for power settings above 60 percent MCP.

Table I

Cessna 172M Noise Data Summary (Ref. 5)

Run	% MCP	RPM	M_H x 10^{-3}	L_A dB	Run	% MCP	RPM	M_H x 10^{-3}	L_A dB
101	72.7	2500	764	68.4	115	81.3	2750	848	77.4
102	73.3	2500	763	68.8	116	79.3	2700	832	76.2
103	77.3	2580	788	71.0	117	64.0	2490	767	68.3
104	79.3	2580	787	72.1	118	77.0	2500	756	71.4
105	86.7	2700	824	74.4	119	-			
106	86.7	2700	824	74.8	120	-			
107	86.7	2700	823	-	121	82.7	2600	784	73.3
108	87.3	2700	824	76.4	122	91.3	2700	816	77.0
109	94.0	2700	824	77.2	123	98.6	2750	830	78.8
110	93.3	2700	824	76.0	124	98.0	2700	813	78.3
111	64.0	2500	771	72.5	125	98.0	2700	813	76.1
112	68.0	2500	769	69.6	126	87.0	2600	784	74.7
113	72.7	2600	802	73.1	127	75.3	2500	756	71.2
114	71.3	2600	800	72.6					

Location: Runs 101-110 Fox
111-117 Big Bear
118-127 Ventura

Table 2

Beech B5-B33 Noise Data Summary (Ref. 5)

Run	% MCP	RPM	M_{H_3} $\times 10^{-3}$	L_A dB	Run	% MCP	RPM	M_{H_3} $\times 10^{-3}$	L_A dB
1	98.7	2600	887	81.9	27	76.4	2580	902	81.7
2	98.7	2600	886	80.1	28	76.9	2570	892	82.9
3	96.4	2550	866	79.5	29	66.7	2560	889	82.0
4	88.0	2560	869	82.0	30	67.1	2570	890	81.7
5	78.7	2560	867	81.9	31	59.1	2560	884	81.2
6	70.2	2560	865	82.1	32	59.6	2570	888	80.3
7	69.8	2560	866	80.6	33	49.8	2550	873	79.8
8	68.0	2560	862	81.5	34	49.3	2550	873	81.4
9	59.6	2580	866	80.4	35	52.0	2300	797	71.0
10	50.7	2550	852	76.3	36	52.0	2300	798	70.5
11	48.9	2290	771	68.9	37	49.3	2100	731	66.7
12	47.1	2080	707	-	38	48.4	2100	733	66.2
13	97.3	2570	879	81.9	39	90.2	2590	894	83.1
14	97.8	2580	882	81.6	40	90.7	2590	895	82.6
15	88.0	2570	880	80.5	41	78.7	2580	892	82.5
16	80.0	2580	874	81.7	42	78.7	2580	890	83.0
17	68.9	2590	876	-	43	68.4	2580	884	81.0
18	60.4	2590	873	-	44	68.4	2580	884	81.9
19	49.8	2550	852	78.5	45	58.7	2580	880	82.2
20	48.4	2290	775	68.7	46	58.7	2580	884	81.9
21	48.0	2100	717	65.8	47	49.3	2580	874	80.9
22	96.9	2560	874	81.0	48	49.3	2580	876	81.1
23	47.1	2100	715	65.6	49	49.3	2300	790	70.5
24	68.4	2580	872	81.9	50	49.3	2300	789	69.7
25	60.0	2580	872	82.3	51	48.0	2100	727	64.9
26	50.2	2550	852	82.8	52	47.1	2100	727	65.3

Location: Runs 1-26 Fox
27-38 Big Bear
39-52 Ventura

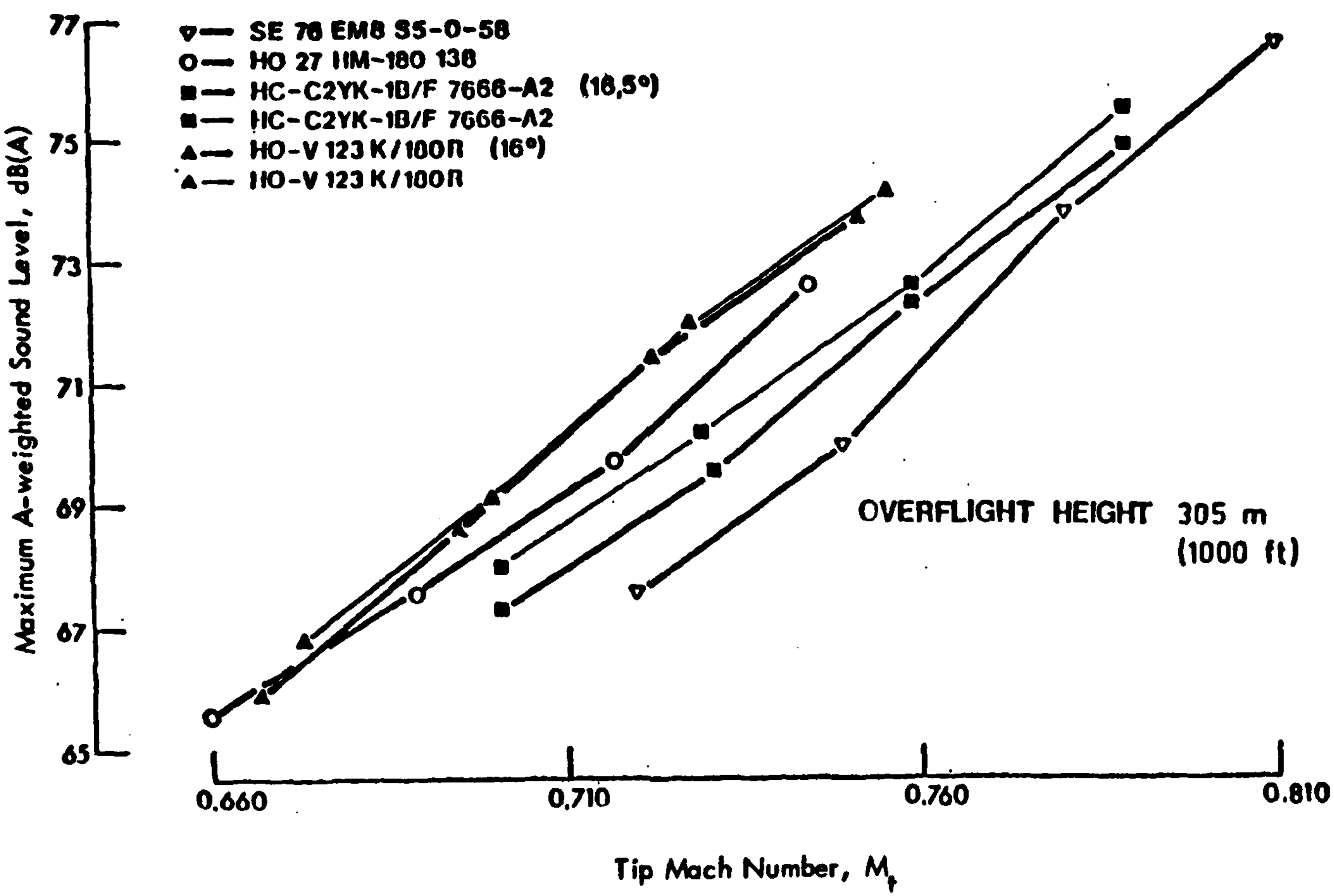

Figure 4. Maximum Average Overflight Noise as a Function of Propeller Tip Mach Number for Turbo-Porter Aircraft (Overflight Test) (From Ref. 6)

These results generally conform with other empirically derived relationships for propeller noise levels expressed in dB(A), PNL,or NC ratings for light aircraft and propeller-driven hovercraft. (These ratings have been used for many years by various aircraft and hovercraft developers to obtain indicative assessments of community noise reaction or aural detectability ratings for their vehicle designs. The results are not usually published in equation form.) The general trend of such results is:

$$\begin{aligned} \text{Noise Rating} \propto\ & (150 \text{ to } 250) \log (M_t) \\ & + (2 \text{ to } 10) \log (BHP) \\ & + (5 \text{ to } 10) \log (D/B) \end{aligned}$$

where M_t is the blade tip Mach number,

BHP is the brake horsepower,

D is the propeller diameter, and

B is the number of blades.

Obviously, the large range of values for the coefficient of each term leaves much to be desired in predictive work; this occurs because each version of the equation has been derived separately for a particular type of application.

The second set of referenced data,[6] shown in Figure 4, was obtained by performing flyover tests of a Turbo-Porter airplane with different propellers installed for each test series. While the available information (in the cited reference) regarding test conditions is incomplete, the noise data for each test series are averages of the maximum A-weighted sound levels obtained from 1000 ft. height flyover tests at each tip speed condition. These data will be shown in Section 2.2.3 to conform generally with the above range of blade tip Mach number dependencies.

In the present study, a semi empirical analysis is performed. Recourse is made to propeller noise theory, which helps to explain the above empirical results and the reasons for the wide range of coefficient values.

2.2.2 Theory

Figure 5 illustrates the typical spectral content of propeller noise. The respective components of the signature are commonly depicted as:

(a) Harmonic, due to rotating steady blade loads,

(b) Harmonic, due to harmonic variations of blade loading, and

(c) "Vortex" noise, this being the broadband random noise arising from random blade loading and caused by the shed vorticity (such as would be shed by a rotating rod).

The last of these descriptions is highly spurious, but the reason behind its terminology is useful, as will be shown later.

The theories for the first two components are of primary interest to the present work, because

(a) the propeller harmonics dominate the A-weighted sound level, and

(b) the dominating range of harmonics (in A-weighted level) is usually of the orders 4 through 12, as shown in Figures 6 and 7.

The first component, due to steady blade loads, is accounted for by the theoretical works of Gutin,[7] and Garrick and Watkins.[8] The rms amplitude of the sound pressure of the m^{th} harmonic is given by

$$P_{mB} = \left| \frac{mBM}{\sqrt{2}\,\pi\, r_1 R} \left[T_{\cos} \theta_1 - \frac{\bar{D}}{M} \right] J_{mB} \; (mBM \sin \theta_1) \right| \qquad (1)$$

where B is the number of blades, R is the blade radius, T and $\bar{D}$ are the thrust and drag forces, respectively, and $M = 0.8\,M_t$. J_{mB} is a Bessel function of the first kind. The terms r_1 and θ_1 are the moving source (retarded) coordinates of the observer position relative to the propeller center and forward axis.

The problem with the above theory is that it predicts a more rapid decay of harmonic level, with harmonic order increase, than occurs in practice. Thus, while the first (fundamental) and second harmonic levels are accurately predicted, the higher-order harmonics and the A-weighted sound level are not.

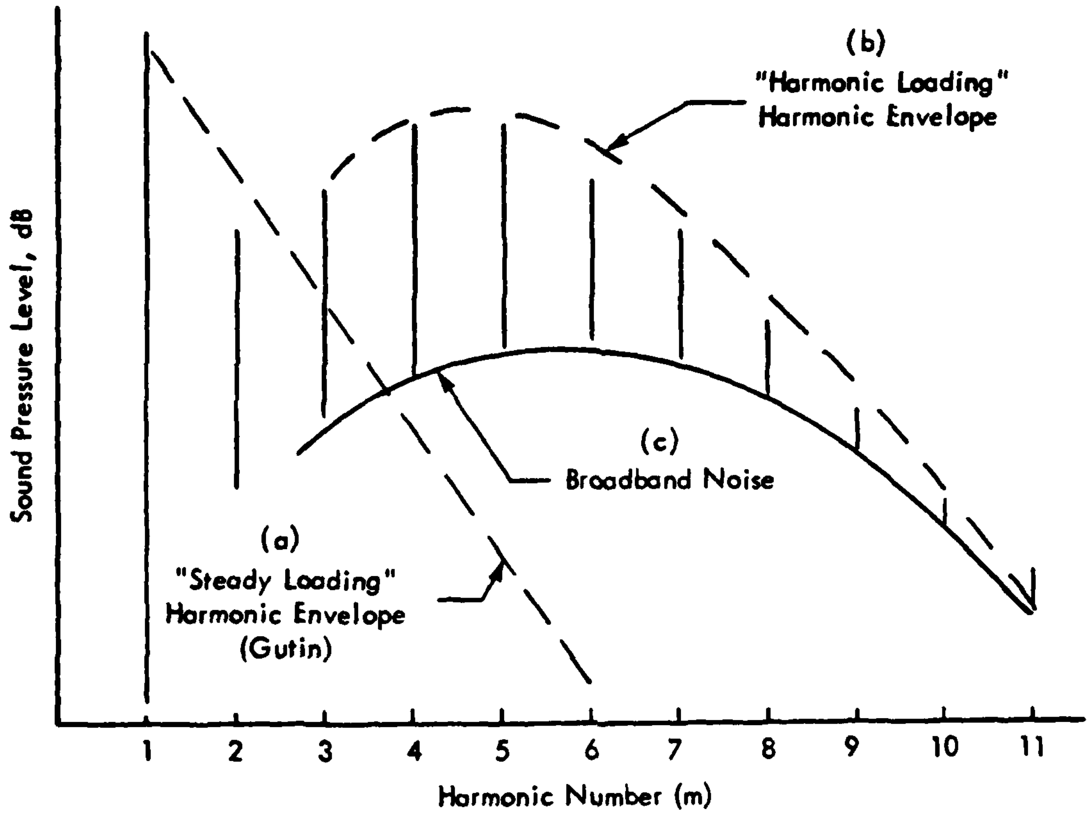

Figure 5. Typical Propeller Noise Spectrum

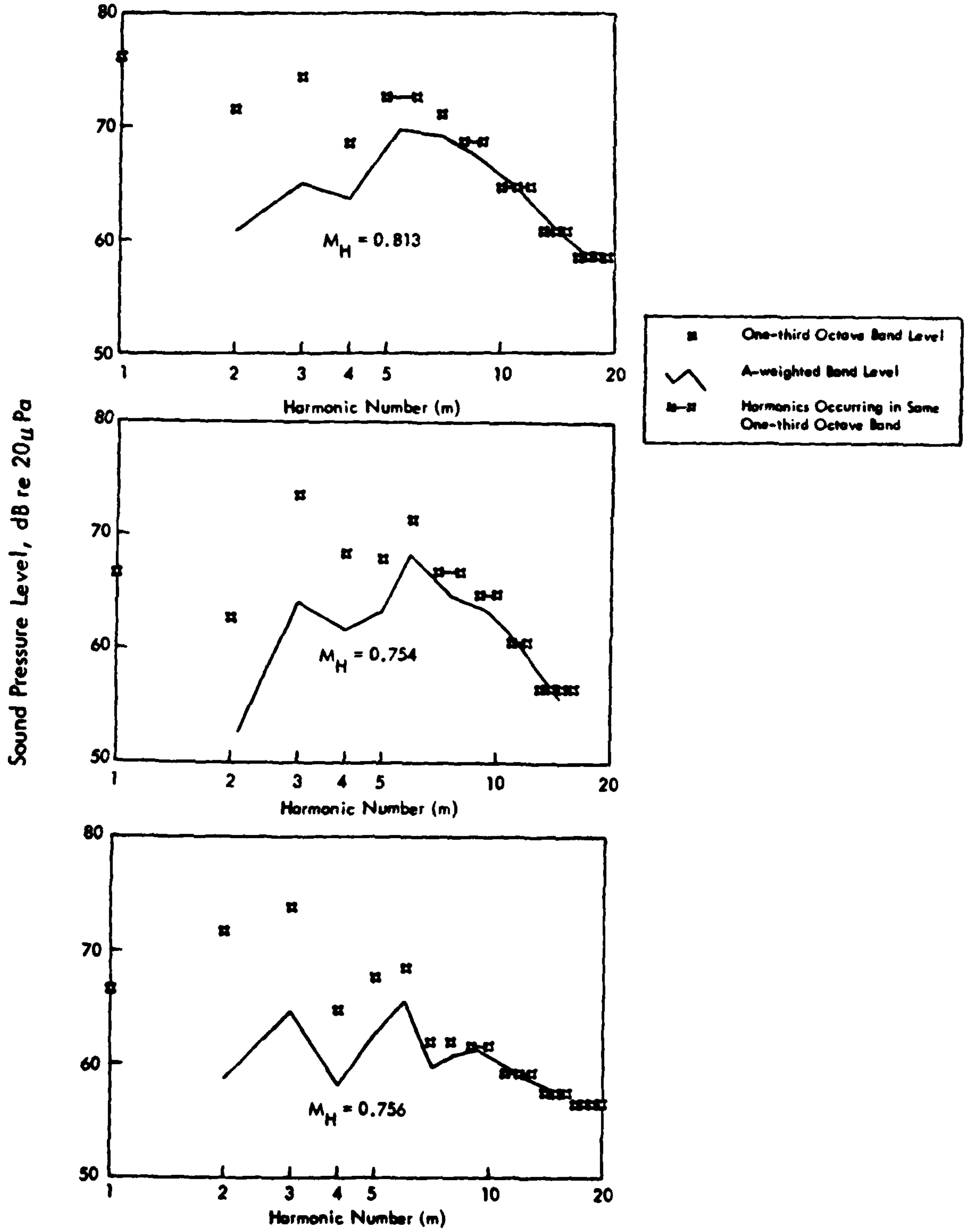

Figure 6 . Frequency Spectra (One-Third Octave Band Levels) of Cessna 172M Aircraft Noise at Propeller Harmonic Intervals (from Ref. 5)

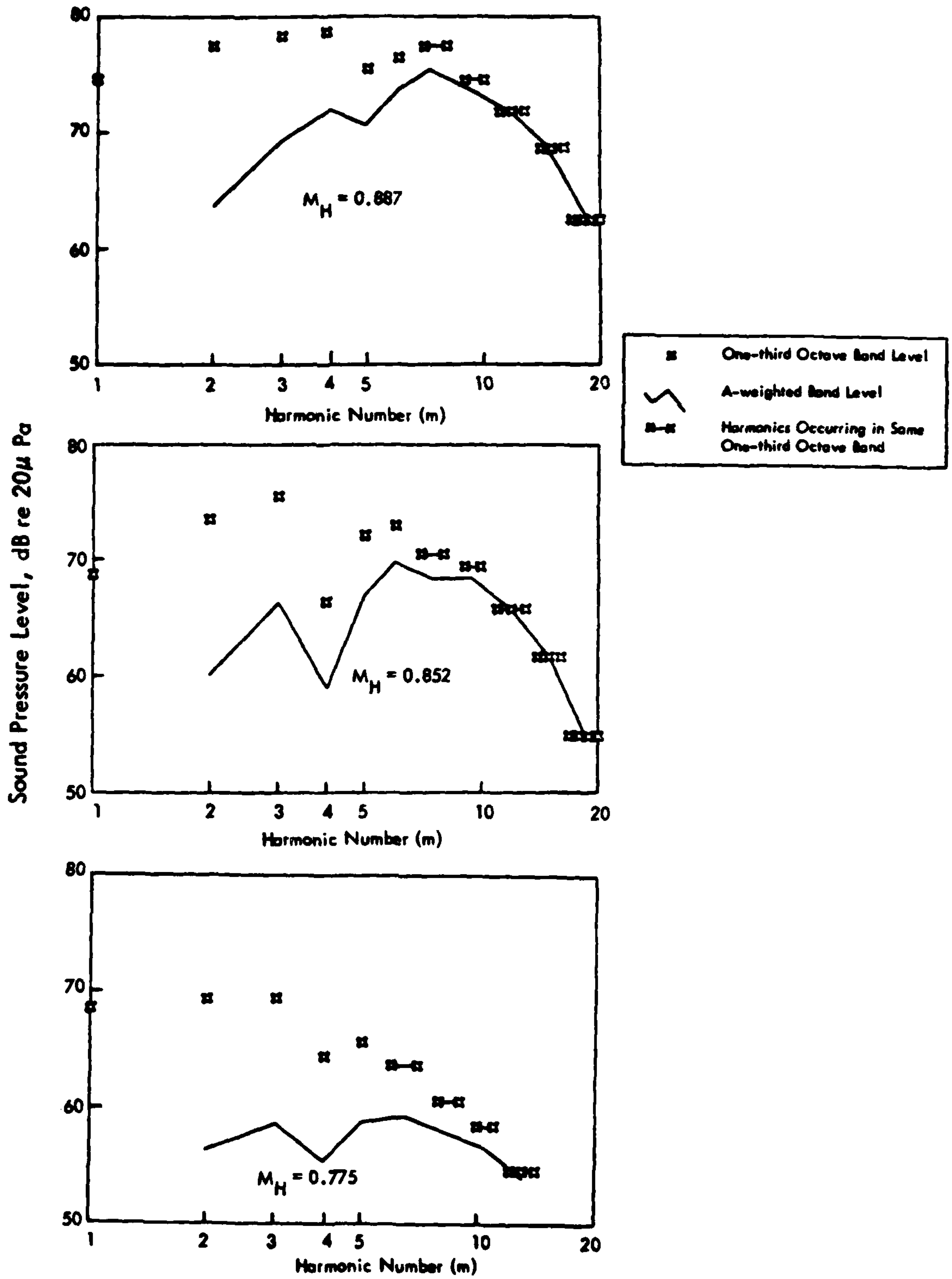

Figure 7. Frequency Spectra (One-Third Octave Band Levels) of Beech B5-B33 Aircraft Noise at Propeller Harmonic Intervals (from Ref. 5)

The high levels of higher-order harmonics can be explained, however, by assuming the occurrence of harmonic variations of blade loads. This effect has been illustrated for hovercraft propeller noise[9] by introducing a cyclic disk loading into the Gutin theory. Figure 8 (from Reference 9) shows the resultant change in spectral content due to different magnitudes of cycle loading (ΔT and $\Delta \bar{D}$) taken as a proportion of the steady thrust (T) and drag (D) on the propeller blades. In this example, a five-lobed (λ = 5) loading pattern was superimposed on the disk of a four-bladed propeller. The "steady loading" sound harmonics (F_λ = 0) are shown to decay rapidly with increase of harmonic number, whereas the addition of a cyclic loading equal to 20 percent of the steady loads (F_λ = 0.2) causes a very significant increase of the third and higher harmonic levels. A further increase of the cycle loading magnitude, to 30 percent of the steady loads (F_λ = 0.3) gives between 1 dB and 4 dB increase in sound levels relative to the 20 percent loading case. In the Reference 9 study, the cyclic loadings were introduced into a more basic form of the Gutin equation (Eq. 1) which required a mathematical integration to be performed around the disk circumference. The exact theory, developed for axial compressor noise[10] and later applied to helicopter rotor noise,[11] is similar in form to the Gutin equation. For harmonic loading, the rms pressure is given by

$$p_{mB} = \left| \frac{mBM}{\sqrt{2}\,\pi\, r_1 R} \sum_{mB-\lambda} \left(T_\lambda \cos\theta_1 - \frac{\bar{D}_\lambda}{M}\right) J_{mB-\lambda}(mBM \sin\theta) \right| \qquad (2)$$

where λ is the loading harmonic order, T_λ and $\bar{D}_\lambda$ are the respective thrust and drag <u>harmonic</u> loads.

While it is difficult to quantify such loadings for a light airplane, it is important to recognize that

(a) any asymmetry in the airflow through the propeller disk can be represented as a harmonic series, and

(b) the observed noise data for light aircraft propellers strongly suggests that such loading effects do exist.

The general principles of this propeller noise theory are therefore used here to interpret the test data contained in References 5 and 6.

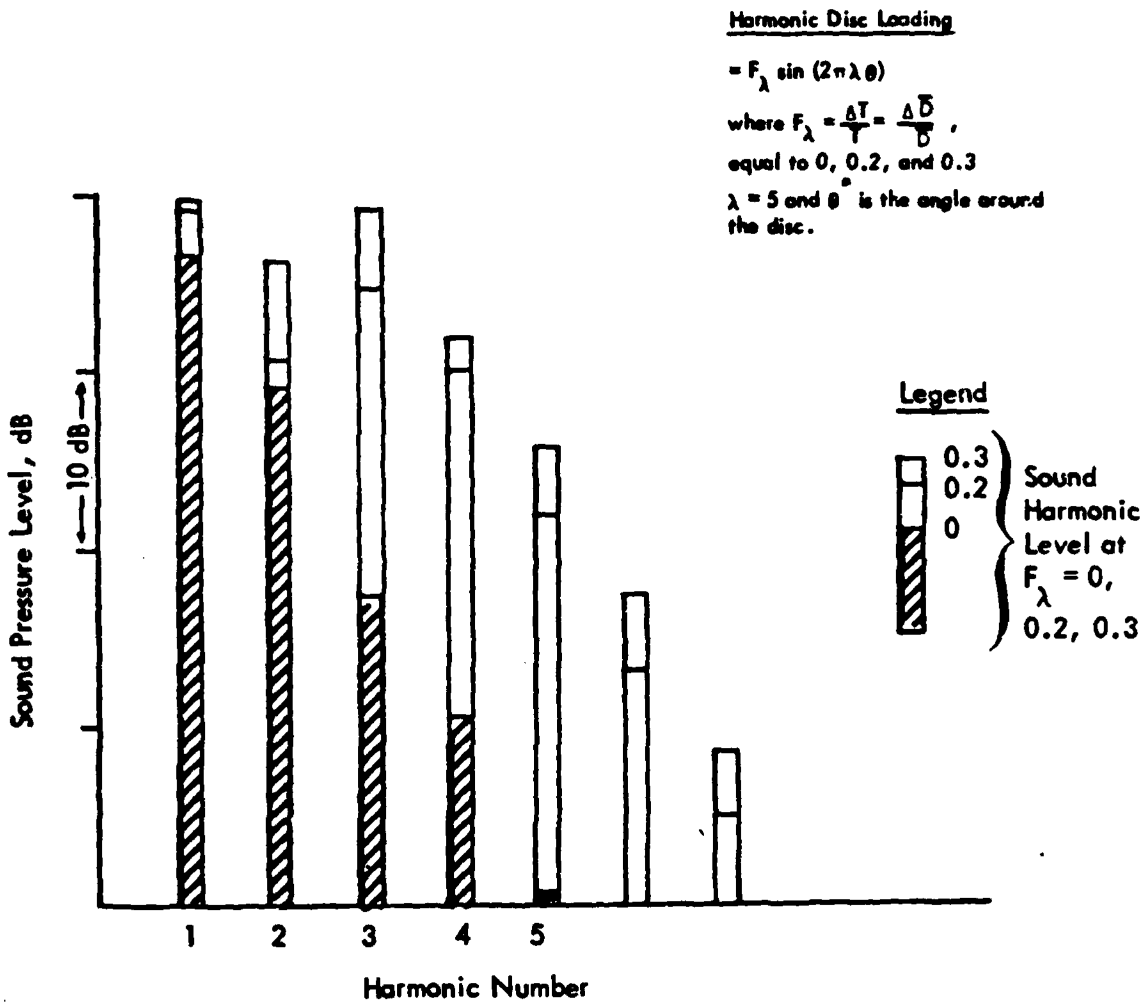

Figure 8. Effect of Disc Harmonic Loading on Propeller Harmonic Noise Levels. (B = 4, Dia. = 9 ft, rpm = 1810)

2.2.3 Effect of Blade Velocity

The A-weighted sound levels for the Cessna and Beech aircraft tests are shown relative to Mach Number ($M = 0.8M_H$) in Figures 9 and 10. Superimposed on these figures are Mach number dependencies relative to M = 0.8, for various values of mB, derived from Eq.(2) by the expression

$$L_{mB}(M) \propto 20 \log_{10} mBM + 10 \log_{10} J^2_{mB} (mBM \sin \theta) \qquad (3)$$

where θ is taken to be 105^o from the forward axis, the typical maximum position for overall noise of propellers. The separate effects of load harmonic amplitude and order are omitted at this stage because nothing is known about them, though they are assumed to exist.

It is seen in these figures that both sets of measured data conform quite well with the slope of the theoretical $L_{mB}(M)$ curve for a value of mB = 12. Also, the corresponding harmonic number, m = 6, for these two-bladed propellers lies in a range noted to be of primary significance to the A-weighted level.

It is also shown in Figures 9 and 10 that Eq.(3) for $L_{mB}(M)$ can be approximated by an equation of the form

$$L_A \propto K_{mB} \log_{10} M \quad ,$$

for M_H greater than 0.7 ($M > 0.56$). The value of K_{mB} obviously changes for different values of mB and it will therefore be necessary to establish some criterion for the selection of a "critical" value (of mB) appropriate to each propeller. Before pursuing this, it is interesting to examine the actual trends of the measured data in terms of the $K \log_{10}M$ dependency.

The data points shown in Figures 9 and 10 are for tests performed at the Ventura airfield only. Linear regression of the data against $\log_{10}M$ in each case gives:

$$L_A \propto 184 \log_{10}M$$

for the Cessna aircraft, and

$$L_A \propto 199 \log_{10}M$$

for the Beech aircraft.

These are reasonably close to the approximate form of Eq.(3) for mB = 12, i.e.,

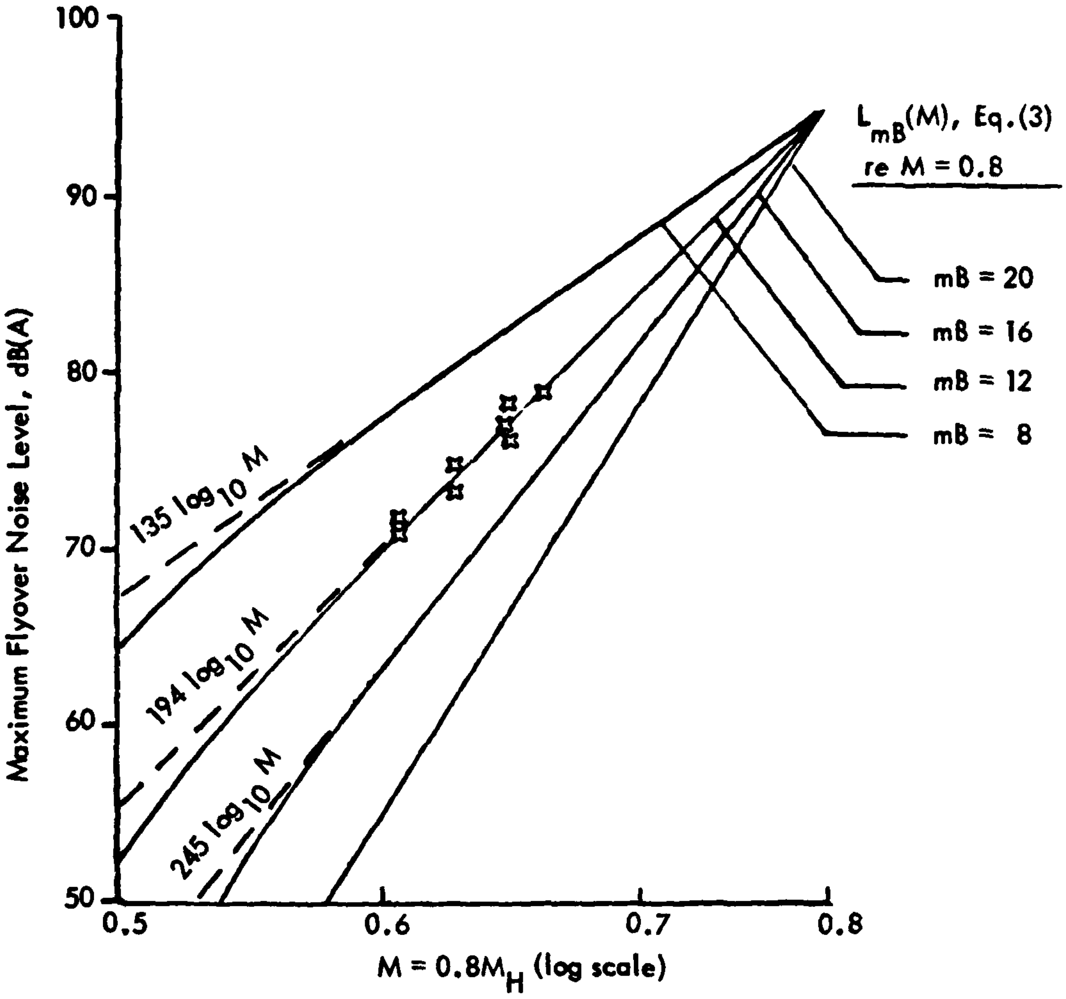

Figure 9. Cessna 172M Flyover Noise Levels Relative to $0.8M_H$ (Data from Reference 5, Ventura Tests)

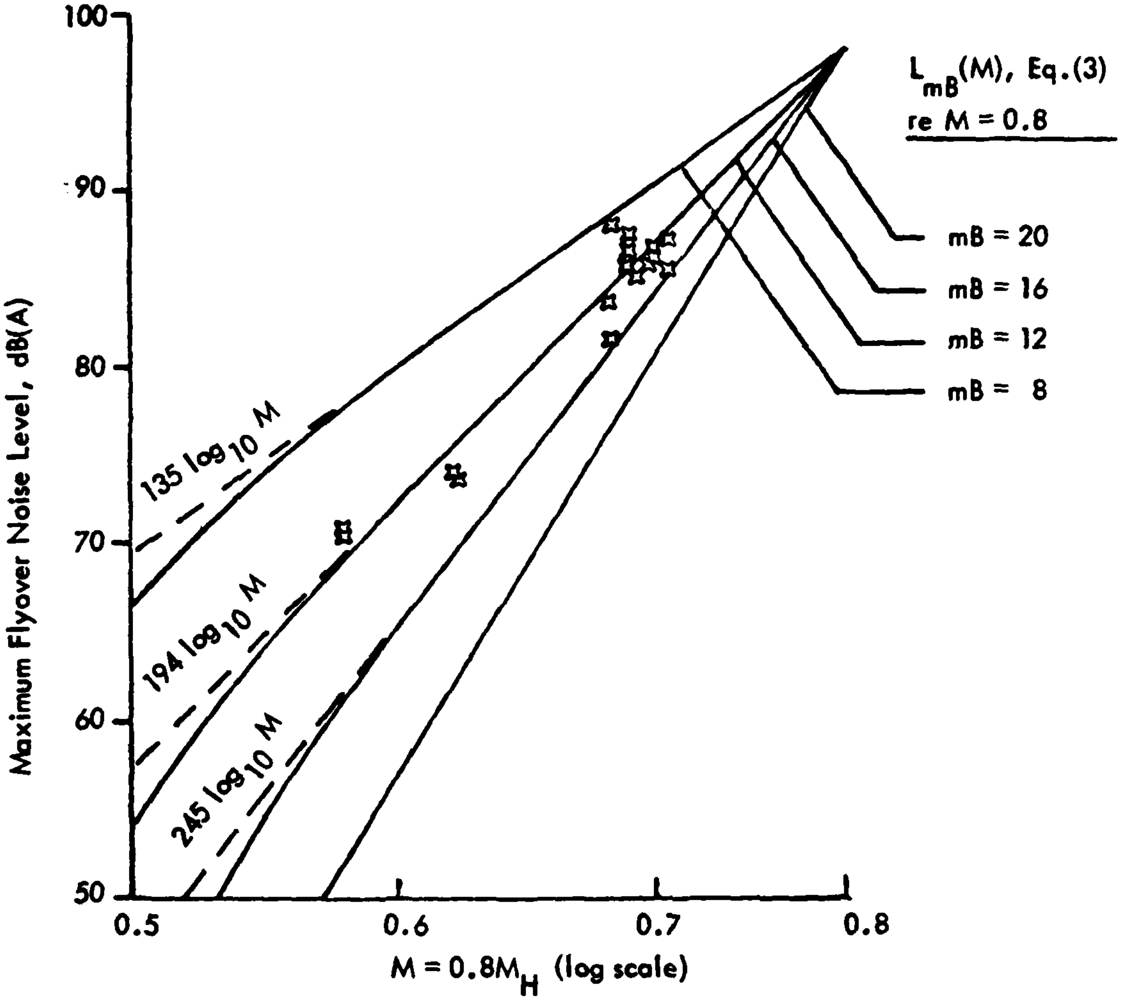

Figure 10. Beech B5-B33 Flyover Noise Levels Relative to $0.8M_H$ (Data from Reference 5, Ventura Tests)

$$L_{mB}(M) \propto 194 \log_{10}M \quad , (mB = 12),$$

as shown in the figures.

By comparison, the empirical results given in Reference 5 for these aircraft were 195 $\log_{10}M_H$ for the Cessna and 240 $\log_{10}M_H$ for the Beech. These are very close to the approximations for $L_{mB}(M)$ with mB equal to 12 and 16, respectively.

i.e.,
$$L_{mB} \propto 194 \log_{10}M \quad , mB = 12$$
$$L_{mB} \propto 245 \log_{10}M \quad , mB = 16.$$

To resolve these dependencies against a wider data base, the Turbo-Porter aircraft noise levels reported in Reference 6 have been similarly analyzed by linear regression of L_A against $\log_{10}M_t$ for each propeller installation. The resultant expressions are as follows:

Propeller Type	$L_A \propto K \log_{10}M_t$
SE 76 EM8 55-0-58	$182.3 \log_{10}M_t$
HO 27 HM-180 138	$133.5 \log_{10}M_t$
HC-CZYK-1B/F (16.5°)	$144.4 \log_{10}M_t$
HC-CZYK-1B/F	$143.8 \log_{10}M_t$
HO-V 123K/180R (16°)	$154.8 \log_{10}M_t$
HO-V 123K/180R	$151.6 \log_{10}M_t$

With the exception of the Sensenich propeller (SE76), these relationships suggest that the corresponding $L_{mB}(M)$ curves would be for lower values of mB (mB = 8 to 10) than for the Cessna and Beech aircraft (mB = 12).

The purpose of the preceding comparisons is to determine whether a quantitative relationship can be developed for sound level dependency on blade Mach number. It is evident that the form,

$$L_A \propto K \log_{10} M \tag{4}$$

requires development of an expression which predicts the coefficient K for each propeller driven airplane. It was suggested earlier, by reference to propeller noise theory, that the coefficient K may be related to some "critical" value of mB for each airplane.

A simplified form of the relationship between K and mB can be obtained from the approximations shown in Figures 9 and 10 for $L_{mB}(M)$. The coefficients for each of the three examples (i.e., mB = 8, 12 and 16) are as follows:

mB	K_{mB}
8	135
12	194
16	245

Taking the range of mB from 8 to 16 to be the primary range of interest, K_{mB} can be estimated, from these three values, with an accuracy in the value of K_{mB} itself of +0, -5 by the expression

$$K_{mB} = 135 + 365 \log_{10} \left(\frac{mB_c}{8} \right) , \tag{5}$$

where mB_c is the critical value of mB.

The consequent requirement is therefore to be able to predict mB_c for any particular propeller.

Some clue to this can be derived by reference to studies of propeller "vortex noise."[12, 13] In the earlier of these,[12] the noise radiated by rotating rods was found to have a spectral maximum at the vortex-shedding (Strouhal) frequency

$$f_s = 0.2\ V_t/d \tag{6}$$

where 0.2 is the Strouhal number, V_t is the tip speed, and d is the rod (or wake) thickness. For propeller noise[13] it was found that one-third octave band spectra exhibited a similar peak at the Strouhal frequency, when wake thickness was represented by the frontal-projected width of the blade. This spectral peak region is now known to contain harmonic noise and may therefore give an indication of the associated critical mB value.

It is therefore assumed that the critical harmonic order, m_c, may be estimated by

$$m_c = f_s/f_1 \tag{7}$$

where f_1 is the blade passage frequency (= rpm x B/60).

Substituting $f_s = \frac{0.2\,\pi\,D(\mathrm{rpm})}{60d}$

into Eq.(7) gives

$$m_c = \frac{0.2\,\pi\,D}{d\,B}$$

and therefore,

$$mB_c = \frac{0.2\,\pi\,D}{d} \tag{8}$$

The applicability of Eq.(8) to the problem of predicting K (Eq.5) is tested by substitution in four of the noise data cases where propeller geometry information has been obtained from the manufacturers. In these cases, the value of d is taken to be the blade width at the 80 percent radius station. The resulting estimates of K_{mB}, obtained from Eqs.(8) and (5), are compared with the corresponding K values derived from the noise data as follows:

Aircraft Type	Propeller Type	d (in.)	D (in.)	mB_c (Eq. 8)		K_{mB} Predicted	K Actual
Cessna	McCauley[a]	4.4	75	11	(10.7)	185.5	184.0
Beech	McCauley[b]	5.5	84	10	(9.6)	170.4	199.0
Porter	Sensenich[a]	4.5	76	11	(10.6)	185.5	182.3
Porter	Hartzell[b]	5.7	74	8	(8.2)	135.0	143.8

Note: (a) 2-bladed, fixed pitch propellers.
(b) 2-bladed, variable pitch propellers.

Two values of mB_c are shown for each case. The values in parentheses are for mB_c rounded off to the first decimal; the other values are for mB_c rounded off to the nearest integer value. It will be noted that mB_c is not rounded to the nearest even-numbered integer value, as would be expected for a 2-bladed propeller (B=2). This is because the need is for a representative value of mB_c which can be used to predict the dependency of L_A on blade speed. This value can be assumed to represent the range of harmonics which control the A-weighted sound level, rather than being a specific propeller-harmonic order.

The predicted values of K_{mB} are seen to be in reasonable agreement with the actual values for three of the four data cases. The exception is for the Beech aircraft, where the actual coefficient is significantly greater than the predicted value and is contrary to the general trend of the other cases. No explanation of this can be offered at present. However, the mean error over all five cases is

-1.0 dB(A) when the predicted value of K_{mB} is used (instead of the actual K) to extrapolate noise data from a tip Mach number of 0.7 to a Mach number of 0.9. Omitting the Beech aircraft case, the mean error is -0.4 dB(A). Considering that this tip Mach number range is probably wider than would typically be required for blade velocity corrections, the method derived above would appear to be adequate for present purposes.

It should be noted that although the value of M has been taken as $0.8M_t$ or $0.8M_H$ for the respective reference data sets, the form of the correction for relative effects of blade velocity need only be based on either M_t or M_H (without the factor of 0.8). The selection of M_t or M_H is discussed in Section 2.2.4. Meanwhile, the basic result of the blade velocity effects examined here can be summarized as:

$$L_A \propto K \log_{10} M \tag{9}$$

where

$$K = 135 + 365 \log \left(\frac{0.2 \pi D}{8 b_{0.8}} \right) ,$$

or, more simply $$K = 365 \log (D/b_{0.8}) - 268$$

where D is the propeller diameter and

$b_{0.8}$ is the blade width at 0.8 radius (previously denoted as d).

2.2.4 Effect of Forward Speed

The effect of forward speed can be expected to play two separate roles in influencing measured noise levels. First, the effective airflow velocity over the blades will be more closely approximated by the helical speed. Second, there is a continuous rate of change of distance between the source (the propeller) and the measurement position during the flyover. Both of these effects can be expected to give an increase of sound level as forward speed is increased. However, in each case, where the aircraft is within a margin of 70 percent of its maximum power flight speed, the net difference due to this effect is small (<1 dB) compared with the relative tip speed effect.

For example, consider two flight cases where the aircraft's forward speed V_x is decreased by reducing propeller rpm. The resulting changes in V_x, M_t and M_H are as follows:

Condition	RPM	V_x (fps)	M_t	M_H
Maximum power	2600	251	0.857	0.886
Reduced power	2290	175	0.755	0.771

Application of Eq.(9) to these cases predicts a noise level change of 9.4 dB between the maximum and reduced power cases when only the rotational tip Mach number M_t is used. On the other hand, substitution of the helical tip Mach number M_H in Eq.(9) gives an expected noise level change of 10.3 dB (K, by both cases, was 170.4). The difference between these estimates, 0.9 dB, represents the added effect of forward motion when the helical, instead of rotational tip Mach number, is used in Eq.(9). Although the available data base is inadequate to completely validate this method for estimating the influence of forward speed, it is considered the most accurate approach available at this time.

For the sake of comparison, the additive effect due to forward motion of the propeller relative to the measurement position might be approximated from the theory of the sound field of a moving simple source. Although an exact analytical expression can be derived for the maximum level observed by a stationary receiver for such a case, numerical analyses for this problem reveals that the change in maximum sound level due to forward motion could be closely approximated by[14]

$$\Delta \simeq +30 \log \left[1/(1 - M^2)\right] \quad ,\text{dB} \qquad (10)$$

where M would be taken as the Mach number of the aircraft itself.

Applying this concept to the above cases gives an estimated noise level change due to forward motion of only 0.4 dB, compared with 0.9 dB for the helical motion effects.

In the context of correcting noise levels from an off-reference condition, it is suggested that applying both of these corrections for forward motion may incur some penalty, giving an exaggerated reference noise level. Thus, the use of helical Mach number in Eq.(9), and omission of any $(1 - M_x^2)$ correction, would appear to be a suitable compromise which conforms with current practice in reporting noise levels.

2.2.5 Effect of Power Setting

The preceding analysis of effects of tip speed changes on propeller noise has neglected any possible influences of power setting (e.g., brake horsepower or thrust). The latter effects are usually obscured in tests of fixed-pitch propellers, where the power setting is directly governed by the rpm. Variable-pitch propellers obviously allow the capability of reducing power loading at any given rpm and therefore should provide guidance on the quantitative nature of loading effects.

Reference is therefore made to the flyover noise data obtained for the Beech B5-B33 airplane, which has a McCauley variable-pitch, 2-bladed propeller. These data, reproduced in Table 2, were obtained at three different airfields (with different altitude densities) and therefore need to be considered as comprising three separate data sets.

These data can be examined in two ways. The first is to examine the given data with respect to changes in power setting for each (constant) tip speed setting. The second is to correct the noise levels for tip speed variations and examine each complete set for residual correlation (of the corrected results) with power settings.

Table 3 is presented for the former purpose. The inherent variability of the data, across each power range, signified in the table by the standard deviation σ_n, is such that a definitive regression of the data against %MCP would not be conclusive.

Table 3

Comparison of Power Setting with Noise Level

(Constant RPM Cases, 1000 ft. Flyover, Beech B5-B33)

(Data from Reference 5)

RPM	2550		2560		2570		2580	
Field	%MCP	L_A	%MCP	L_A	%MCP	L_A	%MCP	L_A
Ventura	96.4	79.5	96.9	81.0			97.8	81.6
	50.7	76.3	88.0	82.0			80.0	81.7
	50.2	82.8	78.7	81.9			68.4	81.9
	49.8	78.5	70.2	82.1			60.0	82.3
			69.8	80.6			59.6	80.4
			68.0	81.5				
	$\sigma_n = 2.34$		$\sigma_n = 0.55$				$\sigma_n = 0.64$	
Big Bear			66.7	82.0	76.9	82.9		
			59.1	81.2	67.1	81.7		
					59.6	80.3		
			$\sigma_n = 0.40$		$\sigma_n = 1.06$			
Fox							78.7	82.5
							78.7	83.0
							68.4	81.0
							68.4	81.9
							58.7	82.2
							58.7	81.9
							49.3	80.9
							49.3	81.1
							$\sigma_n = 0.71$	

Table 4 is a compilation of all of the Table 2 data, with L_A corrected to a nominal value of $M_H = 0.887$ by means of Eq.(9). (That is, L_A (corrected) = L_A (measured) - 170.4 log (M_H/0.887).) As indicated by the standard deviation σ_n of the corrected data for each airfield, there is still a substantial variability which one would like to further reduce by applying some correction for power setting. For clarity, the average corrected levels in each power range are shown in Figure 11 relative to percent maximum continuous power (MCP). The general trend, as indicated by approximate curves through the data, is towards higher noise levels at power settings in the region of 70% MCP, than at lower or higher powers. Neglecting power settings below 70% MCP (that is, assuming tests at such lower power settings would not be permitted in noise certification programs), there is insufficient evidence in these example cases to justify any correction for power setting changes between 70% and 100% MCP. (The relative trends of the Figure 11 data with respect to airfield characteristics are examined in Section 2.2.6.)

These results do not, however, include all of the dependence of noise level on blade loading. Scaling laws for propeller performance are typically based on a propeller performance coefficient of the form

$$C_F = \frac{F}{\rho n^2 D^4} \tag{11}$$

where

ρ is air density, n is rotational speed, and D is the propeller diameter.

If the assumption is made that changes in power setting, at constant rpm (n), are represented by changes in C_F, then the relatively weak dependence of noise level on power setting is simply that associated with changes in C_F. Thus, for a fixed pitch propeller, or a variable pitch propeller operated at a pitch close to its maximum power setting, the variation of noise level due to force (thrust or drag) effects will be observed as part of the blade speed dependence.

The effect of propeller forces being proportional to $\rho n^2 D^4$ has relevance in another context, however, as discussed in the following subsection.

Table 4

Beech B5-B33 Noise Data (from Ref. 5)

(corrected by Eq.(9) to $M_H = 0.887$)*

Ventura Airfield

%MCP	L_A^*
98.7	81.9
98.7	80.2
96.4	81.3
88.0	83.5
78.7	83.6
70.2	84.0
69.8	82.4
68.0	83.6
59.6	82.2
50.7	79.3
48.9	79.3
97.3	82.6
97.8	82.0
88.0	81.1
80.0	82.8
49.8	81.5
48.4	78.7
48.0	81.5
96.9	82.1
47.1	81.6
68.4	83.2
60.0	83.6
50.2	85.8
Mean	81.9
σ_n	1.46

Big Bear Airfield

%MCP	L_A^*
76.4	80.5
76.9	82.5
66.7	81.8
67.1	81.5
59.1	81.5
59.6	80.2
49.8	81.0
49.3	82.6
52.0	78.9
52.0	78.3
49.3	81.0
48.4	80.3
Mean	80.8
σ_n	1.25

Fox Airfield

%MCP	L_A^*
90.2	82.5
90.7	81.9
78.7	82.1
78.7	82.8
68.4	81.3
68.4	82.2
58.7	82.8
58.7	82.2
49.3	81.2
49.3	82.0
49.3	79.1
49.3	78.4
48.0	79.6
47.1	80.0
Mean	81.3
σ_n	1.39

$^*L_A = L_A - 170.4 \log \left(\frac{M_H}{0.887}\right)$, dB

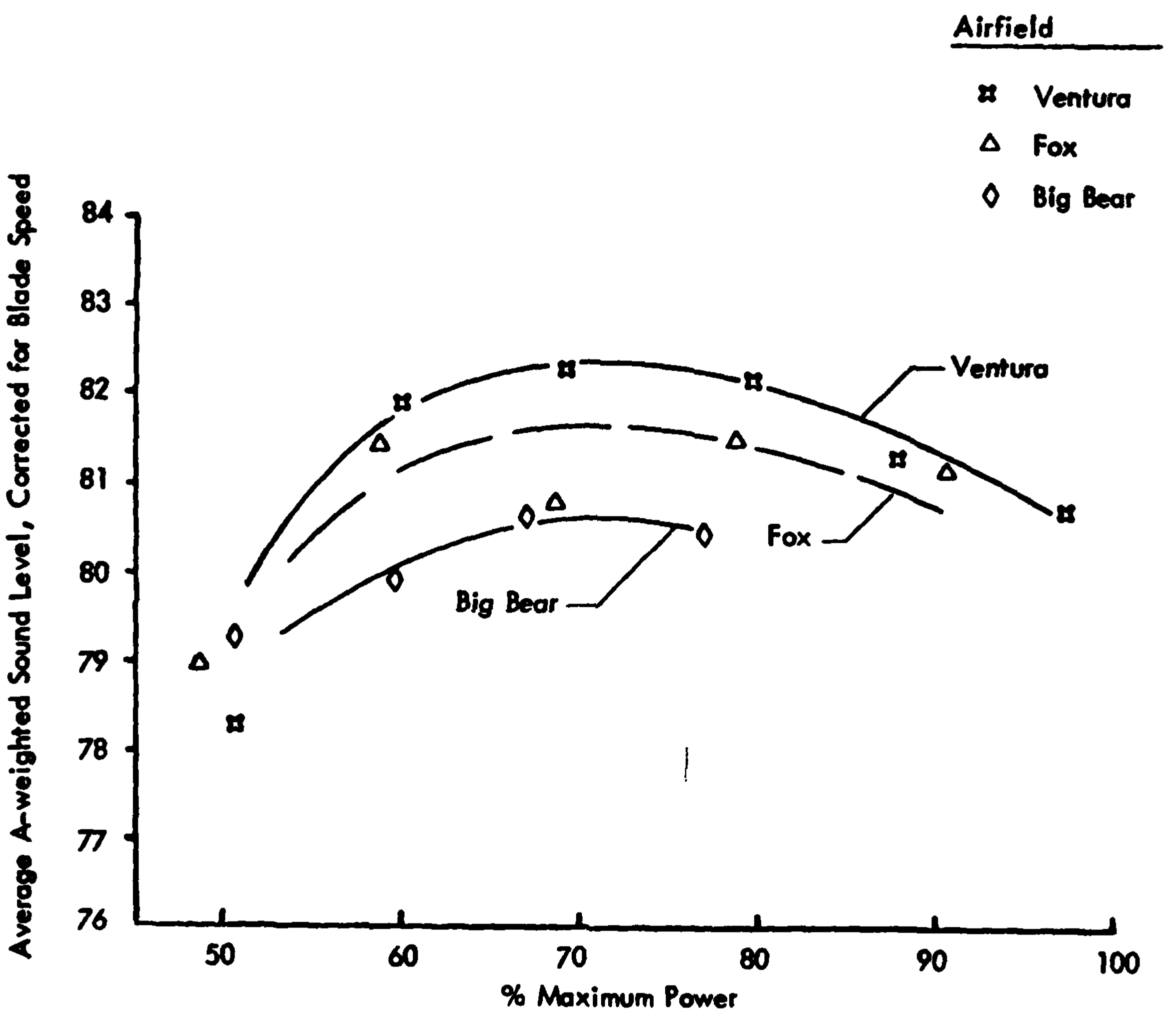

Figure 11 . General Trend for Variation of L_A, Corrected for Blade Speed Effect, with Percentage of Maximum Power (B5-B33 Aircraft) (Data derived from Ref. 5)

2.2.6 Effect of Test Altitude

The preceding examination of operational parameters, in relation to flyover noise levels, has treated changes of these parameters as occurring at unchanged atmospheric conditions. The test data[5] for the Beech and Cessna airplanes has therefore been considered as comprising six subsets of data, each subset being for the specific aircraft at one of the three test airfields. Similarly, the Turbo-Porter data[6] has been assumed to have been acquired under constant atmospheric conditions for each installed propeller.

The implication of Eq.(11) is that atmospheric conditions will affect the sound generated by a propeller. The more obvious effect is that of air density (ρ). However, if the blade forces are proportional to V^2 rather than M^2, and are already included in the derived expressions for $L_A \propto K \log_{10} M_H$, then there is a need to account for the speed of sound (c_o).

Whereas Eq.(9) gives the A-weighted sound pressure, p_A, to be related to helical Mach number by

$$p_A \propto M_H{}^{K/2} \tag{12}$$

where K is the exponent defined by Eq.(9), the incorporation of the scaling law (Eq. 11) would suggest that this should be modified to

$$p_A \propto \rho c_o{}^2 M_H{}^{K/2} \tag{13}$$

That is, the blade loading part inherent in Eq.(12) is converted from M^2 to V^2 by the inclusion of $c_o{}^2$.

Referring now to the subsets of data for the Cessna and Beech aircraft, as summarized in Table 5, it is seen that the average noise levels (corrected by Eq.(9) for helical Mach number) decrease as test density altitude increases. This trend is consistent with a dependency on air density, speed of sound, or both, in the three field cases. Application of a $-20 \log_{10}(\rho c_o{}^2)$ correction, referred to the Ventura test conditions, is shown in Table 5 to give reasonable consistency for the Cessna 172M noise data, and a reversed trend for the Beech B5-B33 noise data. However,

Table 5

Summary of Corrected Noise Levels for Each of Three Airfields at Different Altitudes

(based on data from Ref. 5)

	Airfield		
	Ventura	Fox	Big Bear
Field Elevation	41	2350	6750
Test pressure altitude (ft)	875	3130	7500
Test density altitude (ft)	1000	3500	8100
Test density ratio, σ	0.972	0.899	0.783
Test sound speed, fps^{-1}	1117	1111	1098
Cessna 172M Noise Levels			
Corrected according to Eq.(9)			
Average Level	77.1	74.3	74.3
Standard Deviation	0.68	0.93	1.08
Beech B5-B33 Noise Levels			
Corrected according to Eq.(9)			
Average Level	81.9	81.3	80.8
Standard Deviation	1.46	1.39	1.25
$20 \log_{10} (\rho c^2)$ relative to Ventura	0	-0.8	-2.2
Noise Levels corrected by $-20 \log (\rho c^2)$			
Cessna 172M	77.1	75.1	76.5
Beech B5-B33	81.9	82.1	83.0

applying the ρc_o^2 correction to the maximum levels of the curves shown in Figure 11 gives much more consistent results for the Beech aircraft. The respective maximum levels for Ventura, Fox and Big Bear airfields are 82.2, 82.4, and 82.7 dB(A), after applying the 20 log (ρc_o^2) correction, compared with 82.2, 81.3, and 80.5 dB(A) before correction - a decrease of the spread of the maximum levels in Figure 11 between airfields from 1.7 dB to 0.5 dB.

While the preceding analysis cannot be regarded as being fully conclusive on the effects of atmospheric conditions on sound generation by a propeller, the available evidence strongly suggests that the correction derived by means of Eq.(11) should be applied to noise data obtained at conditions where ρc_o^2, or simply the baseline barometric pressure (noting that $\rho c_o^2 = \gamma P_o$), deviates significantly from a reference value at 1000 ft. above sea level.

The final form of Eq.(9), which includes the atmospheric effect, is

$$L_A \propto K \log_{10} (M_H) + 20 \log_{10} (P_o/P_{o\,Ref}) \tag{14}$$

where

K = $365 \log_{10} (D/b_{0.8}) - 268$

M_H = helical tip Mach number

P_o = test barometric pressure (at test altitude)

$P_{o\,Ref}$ = reference barometric pressure at 1000 ft. above sea level

D = propeller diameter, and

$b_{0.8}$ = propeller blade width at 80% radius.

The values of M_H and P_o are to be referred to standard values, M_H being referred to the propeller speed which corresponds to maximum power condition of the airplane at 1000 ft. above sea level, and P_o (the absolute barometric pressure) being referred to the standard atmosphere value at 1000 ft. above sea level.

3.0 EFFECTS OF AMBIENT WEATHER CONDITIONS ON PROPELLER AIRCRAFT NOISE LEVEL

There are two basic effects of ambient weather conditions on the measurement of propeller aircraft noise

- The effect on the sound levels generated by the aircraft noise sources
- The effect on the air-to-ground sound propagation losses

The first effect has been treated in the preceding section where it was shown that a correction for ambient pressure is beneficial.

This section is concerned, then, with only the effect of nonstandard conditions on the air-to-ground *propagation* losses. Furthermore, this will reduce to consideration only of changes in propagation loss due to the variation with weather in atmospheric absorption in still air. (In this case, "weather" is interpreted to mean only ambient temperature and humidity.) The normal variation in the acoustic impedance (ρc) *along the* propagation path, for a standard atmosphere,[15] would not be expected to change the observed sound pressure level on the ground by more than 0.15 dB for a source located 1000 ft above sea level. Hence, normal deviations from this standard atmosphere could only cause negligible effects on the received level *for a source* nominally located at 1000 ft. Thus, ρc effects along the propagation path of propeller *aircraft* noise can be entirely neglected.

3.1 Atmospheric Absorption Effects

The influence of atmospheric absorption is thus the only significant constraint on the ambient window *for certification* of propeller aircraft - not counting any changes in aircraft performance due to weather changes. This influence of atmospheric absorption can be treated by correcting raw measured data for two potential errors:

- For any ambient weather conditions, the change in absorption losses due to deviation of the aircraft flyover altitude from the desired 1000 ft specified in Appendix F of FAR Part 36.[1]
- For a flyover at 1000 ft, the change in level due to deviation of the ambient weather from a standard day at 25°C (77°F) and 70% relative humidity.

The first correction, call it ΔL_R (for changes in the propagation path length R) can be specified by

$$\Delta L_R = L_A' - L_A \qquad , \text{dB} \tag{15}$$

where

L_A' = A-weighted level that would have been measured for a flyover at 1000 ft but at test weather conditions

L_A = "As Measured" A-weighted level at test altitude and weather

The second correction, call it ΔL_W (for changes in weather) can be specified by

$$\Delta L_W = L_A'' - L_A' \qquad , \text{dB} \tag{16}$$

where

L_A'' = the desired A-weighted level that would have been measured for a flyover at the reference altitude (1000 ft) and weather (25°C, 70% relative humidity)

The total correction for off-reference conditions is simply the sum of these two terms which, when added to the "as measured" level, L_A, gives the desired A-weighted level L_A'' corrected back to the reference altitude and weather. That is

$$\begin{aligned} L_A'' &= L_A + \Delta L_R + \Delta L_W \qquad , \text{dB} \\ &= L_A + (L_A' - L_A) + (L_A'' - L_A') \\ &\equiv L_A'' \end{aligned}$$

Each of these correction terms will vary with: (1) the aircraft source spectrum, and (2) the change in atmospheric absorption losses due to deviation of the propagation path length R and weather from reference conditions.

For this analysis of ambient corrections, it was decided to use a single representative aircraft noise spectrum as a reference sound source. (Sensitivity of the final results to this decision is considered later in Section 3.2.4.) This representative spectrum, shown in Figure 12, was selected from a smoothed version

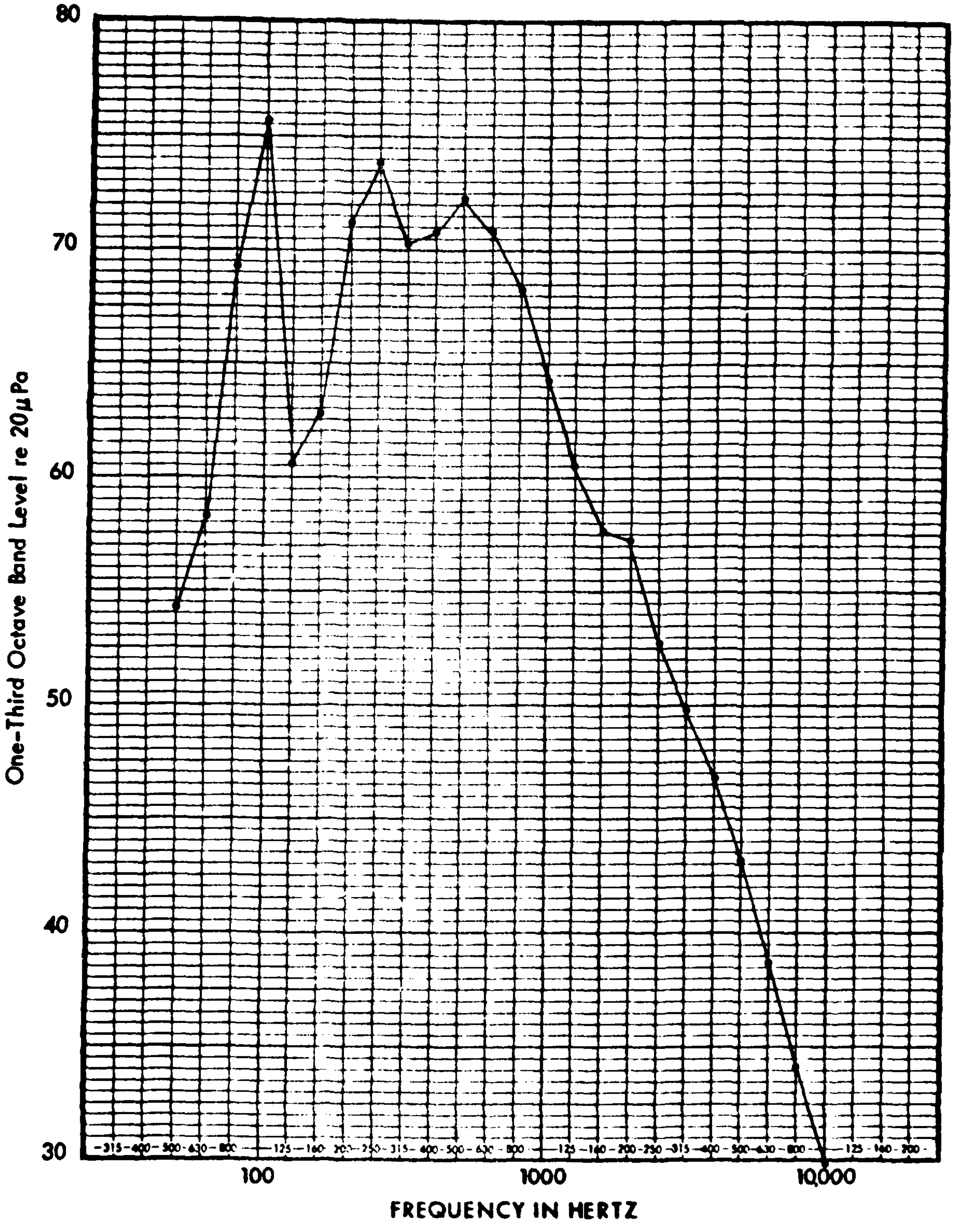

Figure 12. Spectrum of Reference Aircraft Sound Source at 1000 ft., 25°C, 70% Relative Humidity (Data adjusted from Reference 5).

of the actual spectra reported in Reference 5 from the flyover tests of a Cessna 172 aircraft. The raw measured spectra from the latter were first smoothed in the high frequency range and then corrected in a conventional manner using SAE ARP 866A to reference distance and weather conditions to serve as a reference source spectrum. Each of the two correction factors were then computed in the following fashion.

The "as measured" A-weighted noise level, for the most general case where the flyover altitude and weather both differ from standard reference conditions, is given by

$$L_A = 10 \log \left[\sum_{i=1}^{N} 10^{\left[L_{io}(f) + W_i(f) + \alpha_o(f) R_o - \alpha_t(f) R_t \right] /10} \right] ,\text{dB} \quad (17)$$

where

$L_{io}(f)$	=	i^{th} (one-third octave or full octave) band level of standard reference source at frequency f, dB
$W_i(f)$	=	A-weighting at frequency f ,dB
$\alpha_o(f)$	=	Absorption coefficient for standard day (25°C, 70 percent RH) at frequency f, dB/1000 ft
$\alpha_t(f)$	=	Absorption coefficient for "as measured" conditions, at frequency f, dB/1000 ft
R_o	=	reference altitude, 1000's of ft
R_t	=	"as measured" altitude, 1000's of ft

For this formulation, it was assumed that the propagation path length for $L_{A(max)}$ and the aircraft flyover altitude were not significantly different. This is considered a reasonable assumption for propeller aircraft at maximum continuous power conditions where propeller noise dominates and the latter has its strongest directivity close to the propeller disk and hence the dominant propagation path is approximately normal to the aircraft flight path. (If a more exact dominant propagation angle of about 105° had been used, the corresponding values of R_o and R_t would have been multiplied by 1.035.)

3.2 Correction Factors

3.2.1 Correction for Off-Reference Distance, ΔL_R

The distance-corrected A-weighted level, L_A', is obtained from the preceding equation by setting $R_t = R_o$. Then, the value of the distance correction ΔL_R for the A-weighted levels is obtained with Eq. (15).

Tables 6a and 6b provide values of ΔL_R computed in this fashion for R_t = 900 ft and 1100 ft, respectively, for a range of temperature (0 to 40°C) and relative humidity (10 to 100%). Since the absorption coefficients vary with frequency, the overall correction for atmospheric absorption for A-weighted levels cannot be accurately expressed in terms of a single fixed value at one weather condition independent of distance. Thus, Tables 6a and 6b provide separate corrections for distance increments of 100 feet less than (Table 6a) and greater than (Table 6b) the 1000-ft reference altitude. In either case, the net correction is small and can be interpolated linearly for other distance off-sets from the standard reference altitude which are within (or close to) the range of ±100 ft.

Comparing Tables 6a and 6b, it is clear that they are very nearly identical except for sign. This signifies that for a small distance offset of ±100 ft from the reference value, the effective atmospheric absorption correction for the change in A-weighted levels is, as one would expect, nearly linear with distance over the range of 900 to 1100 ft.

3.2.2 Correction for Off-Reference Weather, ΔL_W

The A-weighted level under standard reference conditions, L_A'', is obtained from Eq.(17) by setting both $\alpha_t(f) = \alpha_o(f)$ and $R_t = R_o$. Then, Eq.(16) is used with L_A' computed earlier to determine the weather correction term ΔL_W.

Table 7 provides values of ΔL_W computed in this way for the same range of weather conditions used for Tables 6a and 6b. While it would obviously have been possible to combine Table 7 with either Tables 6a or 6b, it was desirable to leave them separated so that the relative magnitude of the distance and weather corrections could be evaluated individually. Clearly, the weather correction term ΔL_W is more significant than the distance correction term ΔL_R.

Table 6

ΔL_R ATMOSPHERIC ATTENUATION CORRECTION(DISTANCE) - DB/100 FT
BASED ON SAE ARP 866A

VALUES IN TERMS OF RELATIVE A-WTD LVLS

(a) SOURCE-RECVR DISTANCES,(FT)= 1000 (REF), 900 (MEAS'D)

REL. HUM. %	TEMPERATURE - DEG C 0	5	10	15	20	25	30	35	40
100.0	-.03	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
95.0	-.09	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
90.0	-.09	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
85.0	-.09	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
80.0	-.09	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
75.0	-.10	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
70.0	-.10	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
65.0	-.11	-.09	-.09	-.10	-.11	-.12	-.13	-.14	-.15
60.0	-.11	-.10	-.09	-.10	-.11	-.12	-.13	-.14	-.15
55.0	-.12	-.10	-.10	-.10	-.11	-.12	-.13	-.14	-.15
50.0	-.13	-.11	-.10	-.10	-.11	-.12	-.13	-.14	-.15
45.0	-.14	-.12	-.10	-.10	-.11	-.12	-.13	-.14	-.15
40.0	-.15	-.13	-.11	-.10	-.11	-.12	-.13	-.14	-.15
35.0	-.17	-.14	-.12	-.11	-.11	-.12	-.13	-.14	-.15
30.0	-.19	-.16	-.13	-.12	-.11	-.12	-.13	-.14	-.15
25.0	-.22	-.13	-.15	-.13	-.12	-.12	-.13	-.14	-.15
20.0	-.25	-.21	-.13	-.15	-.13	-.12	-.13	-.14	-.15
15.0	-.23	-.26	-.22	-.19	-.16	-.14	-.13	-.14	-.15
10.0	-.26	-.31	-.29	-.25	-.21	-.19	-.16	-.15	-.15

(b) SOURCE-RECVR DISTANCES,(FT)= 1000 (REF), 1100 (MEAS'D)

REL. HUM. %	TEMPERATURE - DEG C 0	5	10	15	20	25	30	35	40
100.0	.03	.03	.09	.10	.11	.12	.13	.14	.15
95.0	.03	.03	.09	.10	.11	.12	.13	.14	.15
90.0	.09	.03	.09	.10	.11	.12	.13	.14	.15
85.0	.09	.09	.09	.10	.11	.12	.13	.14	.15
80.0	.09	.09	.09	.10	.11	.12	.13	.14	.15
75.0	.09	.09	.09	.10	.11	.12	.13	.14	.15
70.0	.10	.09	.09	.10	.11	.12	.13	.14	.15
65.0	.10	.09	.09	.10	.11	.12	.13	.14	.15
60.0	.11	.09	.09	.10	.11	.12	.13	.14	.15
55.0	.12	.10	.09	.10	.11	.12	.13	.14	.15
50.0	.13	.10	.10	.10	.11	.12	.13	.14	.15
45.0	.14	.11	.10	.10	.11	.12	.13	.14	.15
40.0	.15	.12	.11	.10	.11	.12	.13	.14	.15
35.0	.17	.14	.11	.11	.11	.12	.13	.14	.15
30.0	.13	.15	.13	.11	.11	.12	.13	.14	.15
25.0	.21	.17	.15	.12	.12	.12	.13	.14	.15
20.0	.24	.20	.17	.15	.13	.12	.13	.14	.15
15.0	.23	.25	.21	.13	.15	.14	.13	.14	.15
10.0	.25	.30	.23	.24	.21	.13	.16	.15	.15

Table 7

ΔL_W ATMOSPHERIC ATTENUATION CORRECTION(WEATHER) - DB
BASED ON SAE ARP 866A
VALUES RELATIVE TO STD. DAY AT 25 DEG C, 70 % RH
REF. VALUE = 1.098 DB/1000 FT

VALUES IN TERMS OF RELATIVE A-WTD LVLS
REFERENCE SOURCE- RECV'R DISTANCE = 1000 FT

REL. HUM. %	TEMPERATURE - DEG C 0	5	10	15	20	25	30	35	40
100.0	-.31	-.34	-.29	-.20	-.11	.00	.12	.24	.38
95.0	-.29	-.33	-.29	-.20	-.11	.00	.12	.24	.38
90.0	-.25	-.32	-.28	-.20	-.11	.00	.12	.24	.38
85.0	-.22	-.30	-.28	-.20	-.11	.00	.12	.24	.38
80.0	-.17	-.28	-.27	-.20	-.11	.00	.12	.24	.38
75.0	-.13	-.26	-.26	-.20	-.11	.00	.12	.24	.38
70.0	-.07	-.23	-.25	-.20	-.11	.00	.12	.24	.38
65.0	.01	-.19	-.24	-.19	-.10	.00	.12	.24	.38
60.0	.09	-.13	-.21	-.18	-.10	.00	.12	.24	.38
55.0	.19	-.07	-.18	-.17	-.10	.00	.12	.24	.38
50.0	.32	.01	-.14	-.16	-.09	.00	.12	.24	.38
45.0	.46	.13	-.07	-.13	-.08	.00	.12	.24	.38
40.0	.63	.26	.02	-.03	-.07	.01	.12	.24	.38
35.0	.85	.45	.15	-.01	-.04	.02	.12	.24	.38
30.0	1.10	.63	.33	.11	.02	.03	.12	.24	.38
25.0	1.42	.99	.59	.29	.12	.08	.14	.25	.38
20.0	1.72	1.33	.96	.59	.32	.19	.18	.26	.38
15.0	1.91	1.88	1.50	1.08	.72	.46	.32	.32	.40
10.0	1.41	2.16	2.23	1.91	1.49	1.10	.79	.59	.52

Table 8

ΔL_W ATMOSPHERIC ATTENUATION CORRECTION(WEATHER) - DB
BASED ON ANSI S1.26
VALUES RELATIVE TO STD. DAY AT 25 DEG C, 70 % RH
REF. VALUE = 1.092 DB/1000 FT

VALUES IN TERMS OF RELATIVE A-WTD LVLS
REFERENCE SOURCE- RECV'R DISTANCE = 1000 FT
PRESSURE = 1.00 ATM

REL. HUM. %	TEMPERATURE - DEG C 0	5	10	15	20	25	30	35	40
100.0	-.49	-.43	-.39	-.27	-.16	-.09	-.07	-.11	-.17
90.0	-.46	-.46	-.38	-.27	-.15	-.06	-.02	-.04	-.10
80.0	-.41	-.43	-.38	-.26	-.13	-.03	.03	.02	-.02
70.0	-.33	-.40	-.36	-.26	-.12	.00	.08	.10	.07
60.0	-.23	-.34	-.34	-.25	-.12	.02	.13	.18	.17
50.0	-.03	-.24	-.29	-.24	-.12	.04	.17	.26	.29
40.0	.15	-.03	-.20	-.20	-.11	.04	.21	.34	.41
30.0	.54	.20	-.01	-.10	-.07	.05	.22	.39	.53
20.0	1.20	.78	.42	.18	.03	.10	.22	.40	.61
10.0	1.92	1.96	1.61	1.17	.79	.54	.44	.46	.60

3.2.3 Comparison of Corrections Based on SAE ARP 866A and ANSI S1.26

SAE ARP 866A was used to compute the air absorption coefficients[16] employed for constructing Tables 6 and 7. As a matter of current interest, an abbreviated table of ΔL_W - the weather correction term - was also computed using the new ANSI-S1.26 standard[17] for air absorption. The results are given in Table 8. For this table, the pure tone absorption coefficients at the center frequency of each band was used to define the band attenuation. At the distances involved in this analysis, and considering the nature of the source spectrum, errors in the band attenuation due to finite slopes of filter sidebands and finite bandwidths of the filters, discussed at length in Volume III of this report series,[18] are not considered significant and have been ignored for this report.

It is clear from a casual comparison of Tables 7 and 8 that there are differences in the magnitude of the weather correction term ΔL_W, depending on the standard method employed for computing air absorption. The average difference in ΔL_W between the two prediction methods for 27 values between $10^{o}$and 30^{o}C and 20% and 100% relative humdity was -0.09 dB $\pm$0.13 dB. (Applying the ANSI Standard would result in a slightly lower corrected level.) These differences may be greater for typical prop noise spectra than for jet aircraft noise spectra near PNL max due to the tendency for higher sound levels to occur at lower frequencies for prop noise, and it is in this frequency region that the two atmospheric absorption prediction standards differ substantially. Nevertheless, it is clear that the net weather corrections of A-weighted levels are not very different for the two prediction methods. Although the ANSI Standard would be expected to provide much more accurate results for individual low frequency bands and at weather conditions well removed from reference conditions, SAE ARP 866A is still the standard accepted by the aviation industry at this time.

3.2.4 Sensitivity of Results to Source Spectra and Filter Bandwidths

To confirm the generality of the results presented in Tables 6 to 8, values of ΔL_W were also computed for

1. Application of the spectra of Figure 12 in one-third octave bands instead of the full octave band spectra used for computing these tables.

2. Variations of the spectral shape by varying the roll-off rate above 500 Hz to increase or decrease the level at 1000 Hz by $\pm$3 dB and at 8000 Hz by $\pm$12 dB (i.e., increase or decrease the levels at $\pm$3 dB/ octave.

A comparison was made of 27 values of ΔL_W computed with both one-third and full octave band spectra and over a range of weather conditions encompassing $10^{o}C$ temperature intervals from $10^{o}C$ to $30^{o}C$ and 10 percent intervals in relative humidity from 20% to 100%. The mean difference in ΔL_W between the one-third and full octave band spectra was +0.12 dB with a standard deviation of $\pm$0.012 dB.

For the same range of weather conditions, the difference in ΔL_W values, using octave band spectra for the source, but with the two variations in spectral slope defined above, were as follows.

1. Band Levels of Source Spectrum in Figure 12 Decreased above 500 Hz by -3 dB/Octave

Mean Difference	-0.02 dB
Standard Deviation	$\pm$0.85 dB

2. Band Levels Increased above 500 Hz by +3 dB/Octave

Mean Difference	+0.09 dB
Standard Deviation	$\pm$0.18 dB

Thus, considering a 2 sigma limit (95 percent probability in the error), it seems reasonable to expect that Table 7 is valid within at least $\pm$0.4 dB for the average propeller aircraft. (Note, of course, that this is an estimated upper bound to a systematic error that would not be reduced by averaging results from multiple flights for a particular aircraft.)

3.2.5 <u>Potential Correction Procedures</u>

A single algorithm which would describe the correction values embodied in Table 7 does not appear practical. However, it does appear reasonable to consider the following rules for correction of off-reference conditions based on Tables 6 and 7.

ΔL_W - Weather Correction (Aircraft Altitude at 1000 ft)

1. Allow no tests which fall outside a test window bounded as follows: (see Figure 13 for a graphical description).

   - o Temperature not less than $0^{o}C$ or greater than $40^{o}C$.
   - o For temperatures less than $20^{o}C$, a humidity not less than that defined by a line on a linear temperature-humidity plot decreasing from 50% relative humidity at $0^{o}C$ to 20% relative

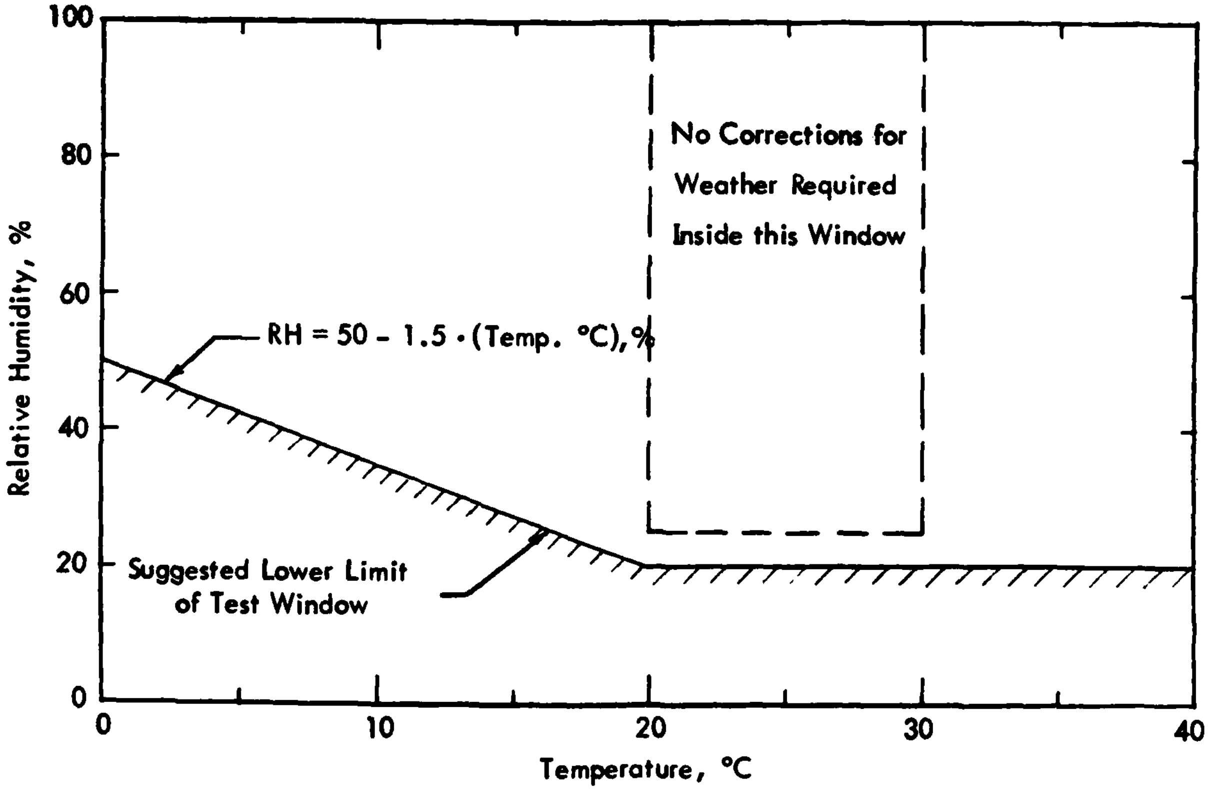

Figure 13. Suggested Ambient Weather Test Window (no tests allowed outside limit between 0 and 40°C, lower humidity limit indicated by hatched line and 100%; no weather correction required for tests conducted inside window bounded by dashed line).

humidity at 20°C. (This lower limit to humidity is defined by the equation; humidity = 50% - 1.5 (Temp. °C), %)

- For temperature equal to or greater than 20°C, a humidity not less than 20%.
- An upper bound of 100% for relative humidity is acceptable according to the results of this analysis; however, an upper bound of 90%, as currently specified in FAR Part 36 may be desirable for other reasons.

This overall weather window should limit any weather correction to less than about 0.4 dB. Except for a region between 5°C and 13°C and for humidity near 30 to 40%, this window is substantially larger than the current window specified in Appendix F of FAR Part 36 of 30 to 90% relative humidity and temperatures between 41°F (50°C) to 86°F (30°C).

2. Within this overall window, no weather correction would be required if the temperature is between 20°C and 30°C, inclusive, and the humidity is not less than 25%. This limits any error due to neglecting weather corrections to less than about $\pm$0.12 dB. (Note that this zero correction window is balanced about zero error and is significantly different than the current condition in Appendix F of FAR Part 36. The latter does not require a weather correction for temperatures from 15 to 25°C and humidity between 40% and the maximum allowed, 90%.)

3. For tests conducted at weather conditions between the limits specified by (1) and (2) above, the correction values specified in Table 7 could be used.

A simpler alternative to the above three rules would be to specify the zero-correction weather window indicated in item (2) above and require use of Table 7 for any conditions outside this window. This is probably acceptable since the probability of test weather conditions falling outside the overall window specified by item 1. above is low.

ΔL_R - Distance Correction (Weather at "As Measured" Conaitions)

4. No correction required if the true aircraft altitude above the ground is within $\pm$30 ft of the 1000 ft reference condition. (This is the same altitude tolerance as currently specified in FAR Part 36 Appendix F and assuming the overall test window specified by item (1) above is adhered to, this should limit the error in measured level due to altitude deviation to less than $\pm$0.05 dB.

5. For altitude deviations greater than $\pm$30 ft, the distance correction could be estimated to within an accuracy of about $\pm$0.3 dB/100 ft by using

$$\Delta L_R \simeq (.0011) \times (\text{Measured Distance (ft)} - 1000) \quad , \text{dB}$$

4.0 CONCLUSIONS

Several aspects of correcting propeller aircraft noise certification data for off-reference conditions were evaluated and the following results obtained:

- Changes in Noise Level Due to Propeller and Aircraft Speed.

  Evaluation of available experimental data led to the development of the following suggested algorithm for a performance correction which should be added to "as measured" levels to account for off-reference propeller and aircraft speed conditions. This algorithm was derived, in part, from theory, and showed good agreement with the limited experimental data available.

$$\Delta L_P = -K \log_{10} (M_H / M_H(\mathrm{Ref})) \quad ,\mathrm{dB}$$

where K = $365 \log_{10} (D/b_{0.8}) - 268$

D = propeller diameter

$b_{0.8}$ = propeller width at 0.8 radius point

M_H = helical tip Mach number

$M_H(\mathrm{Ref})$ = reference helical tip Mach number.

- Changes in Noise Level Due to Engine Power Settings.

  No justification was found for a correction to account for off-reference engine power settings. Available data suggests that noise level is very nearly independent of engine power at power settings of the order of 70 to 90 percent of maximum power.

- Change in Source Noise Level Due to Ambient Pressure.

  The limited available data support the use of the following correction which should be added to "as measured" levels to account for ambient conditions.

$$\Delta L_{TP} = -20 \log \left[\rho c_o^2 (\mathrm{Test}) / \rho c_o^2 (\mathrm{Ref}) \right] \quad ,\mathrm{dB}$$

or, since $\rho c_o^2 \propto$ Barometric Pressure, this reduces to simply

$$\Delta L_{TP} = -20 \log \left[\text{Pressure (Test)/Pressure (Ref)} \right] \quad \text{,dB}$$

For consistency, it would be desirable to set the reference pressure equal to that at a standard day at an elevation of 1000 ft above sea level.

- o Changes in Noise Level Due to Atmospheric Absorption.

  With the use of a generalized spectrum for the maximum A-weighted noise level during certification tests of a propeller aircraft under standard reference conditions (1000 ft altitude, 25°C, 70% relative humidity), tables of the corrections to be added to A-weighted noise level were computed to account for air absorption losses when

  - the aircraft altitude is not at 1000 ft (for any ambient weather condition)
  - the ambient weather is not standard (but the aircraft is at 1000 ft).

The first correction, called ΔL_R, for distance errors, is negligible within the current altitude tolerance of $\pm$30 ft and may be roughly estimated for altitude errors greater than this by

$$\Delta L_R \simeq +0.0011 \left[\text{Test Altitude (ft)} - 1000 \right] \quad \text{,dB}$$

The second correction, called ΔL_W for off-reference weather, cannot be conveniently reduced to a simple algorithm. However, if the ambient weather falls within a test window illustrated in Figure 13 and consisting of temperatures between 20°C - 30°C and relative humidity greater than 25%, the expected correction, based on SAE ARP 866A, should not exceed about $\pm$0.12 dB(A). For weather outside of this minimum window (which differs significantly from a comparable window in Appendix F of FAR Part 36), correction factors are provided in Table 7. It is suggested that these may be applied for weather conditions falling within the overall weather window illustrated in Figure 13 which is, for the most part, significantly larger than that currently specified in Appendix F. Nevertheless, within this suggested new window, based only on variations in atmospheric absorption, the maximum weather correction, ΔL_W, should not exceed about $\pm$0.4 dB(A).

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APPENDIX I

Federal Aviation Regulations, Volume III, Part 36

(Noise Standards: Aircraft Type and
Airworthiness Certification)

Appendix F

"Noise Requirements for Propeller-Driven Small Airplanes"

Appendix F

Noise Requirements for Propeller-Driven-Small Airplanes

PART A—GENERAL

§ F36.1 Scope. This appendix prescribes limiting noise levels, and procedures for measuring noise and correcting noise data, for the propeller driven small airplanes specified in § 36.1.

PART B—NOISE MEASUREMENT

§ F36.101 General test conditions.

(a) The test area must be relatively flat terrain having no excessive sound absorption characteristics such as those caused by thick, matted, or tall grass, by shrubs, or by wooded areas. No obstructions which significantly influence the sound field from the airplane may exist within a conical space above the measurement position, the cone being defined by an axis normal to the ground and by a half-angle 75 degrees from this axis.

(b) The tests must be carried out under the following conditions:

(1) There may be no precipitation.

(2) Relative humidity may not be higher than 90 percent or lower than 30 percent.

(3) Ambient temperature may not be above 86 degrees F. or below 41 degrees F. at 33′ above ground. If the measurement site is within 1 n.m. of an airport thermometer the airport reported temperature may be used.

(4) Reported wind may not be above 10 knots at 33′ above ground. If wind velocities of more than 4 knots are reported, the flight direction must be aligned to within ±15 degrees of wind direction and flights with tail wind and head wind must be made in equal numbers. If the measurement site is within 1 n.m. of an airport anemometer, the airport reported wind may be used.

(5) There may be no temperature inversion or anomalous wind condition that would significantly alter the noise level of the airplane when the noise is recorded at the required measuring point.

(6) The flight test procedures, measuring equipment, and noise measurement procedures must be approved by the FAA.

(7) Sound pressure level data for noise evaluation purposes must be obtained with acoustical equipment that complies with §F36.103 of this appendix.

§ F36.103 Acoustical measurement system.

The acoustical measurement system must consist of approved equipment equivalent to the following:

(a) A microphone system with frequency response compatible with measurement and analysis system accuracy as prescribed in § F36.105 of this appendix.

(b) Tripods or similar microphone mountings that minimize interference with the sound being measured.

(c) Recording and reproducing equipment characteristics, frequency response, and dynamic range compatible with the response and accuracy requirements of § F36.105 of this appendix.

(d) Acoustic calibrators using sine wave or broadband noise of known sound pressure level. If broadband noise is used, the signal must be described in terms of its average and maximum root-mean-square (rms) value for nonoverload signal level.

§ F36.105 Sensing, recording, and reproducing equipment.

(a) The noise produced by the airplane must be recorded. A magnetic tape recorder is acceptable.

[(b) The characteristics of the system must comply with the recommendations in International Electrotechnical Commission (IEC) Publication No. 179, entitled "Precision Sound Level Meters" as incorporated by reference in Part 36 under §36.6 of this Part.]

(c) The response of the complete system to a sensibly plane progressive sinusoidal wave of constant amplitude must lie within the tolerance limits specified in IEC Publication No. 179, dated 1973, over the frequency range 45 to 11,200 Hz.

(d) If limitations of the dynamic range of the equipment make it necessary, high frequency pre-emphasis must be added to the recording channel with the converse de-emphasis on playback. The pre-emphasis must be applied such that the instantaneous recorded sound pressure level of the noise signal between 800 and 11,200 Hz does not vary more than 20 dB between the maximum and minimum one-third octave bands.

(e) If requested by the Administrator, the recorded noise signal must be read through an "A" filter with dynamic characteristics designated "slow," as defined in IEC Publication No. 179, dated 1973. The output signal from the filter must be fed to a rectifying circuit with square law rectification, integrated with time constants for charge and discharge of about 1 second or 800 milliseconds.

(f) The equipment must be acoustically calibrated using facilities for acoustic free-field calibration and if analysis of the tape recording is requested by the Administrator, the analysis equipment shall be electronically calibrated by a method approved by the FAA.

(g) A windscreen must be employed with the microphone during all measurements of aircraft noise when the wind speed is in excess of 6 knots.

§ F36.107 Noise measurement procedures.

(a) The microphones must be oriented in a known direction so that the maximum sound received arrives as nearly as possible in the direction for which the microphones are calibrated. The microphone sensing elements must be approximately 4′ above ground.

(b) Immediately prior to and after each test, a recorded acoustic calibration of the system must be made in the field with an acoustic calibrator for the two purposes of checking system sensitivity and providing an acoustic reference level for the analysis of the sound level data.

(c) The ambient noise, including both acoustical background and electrical noise of the measurement systems, must be recorded and determined in the test area with the system gain set at levels that will be used for aircraft noise measurements. If aircraft sound pressure levels do not exceed the background sound pressure levels by at least 10 dB(A), approved corrections for the contribution of background sound pressure level to the observed sound pressure level must be applied.

§ F36.109 Data recording, reporting, and approval.

(a) Data representing physical measurements or corrections to measured data must be recorded in permanent form and appended to the record except that corrections to measurements for normal equipment response deviations need not be reported. All other corrections must be approved. Estimates must be made of the individual errors inherent in each of the operations employed in obtaining the final data.

(b) Measured and corrected sound pressure levels obtained with equipment conforming to the specifications described in § F36.105 of this appendix must be reported.

(c) The type of equipment used for measurement and analysis of all acoustical, airplane performance, and meteorological data must be reported.

(d) The following atmospheric data, measured immediately before, after, or during each

test at the observation points prescribed in § F36.101 of this appendix must be reported:

(1) Air temperature and relative humidity.

(2) Maximum, minimum, and average wind velocities.

(e) Comments on local topography, ground cover, and events that might interfere with sound recordings must be reported.

(f) The following airplane information must be reported:

(1) Type, model and serial numbers (if any) of airplanes, engines, and propellers.

(2) Any modifications or nonstandard equipment likely to affect the noise characteristics of the airplane.

(3) Maximum certificated takeoff weights.

(4) Airspeed in knots for each overflight of the measuring point.

(5) Engine performance in terms of revolutions per minute and other relevant parameters for each overflight.

(6) Aircraft height in feet determined by a calibrated altimeter in the aircraft, approved photographic techniques, or approved tracking facilities.

(g) Aircraft speed and position and engine performance parameters must be recorded at an approved sampling rate sufficient to ensure compliance with the test procedures and conditions of this appendix.

§ F36.111 Flight procedures.

(a) Tests to demonstrate compliance with the noise level requirements of this appendix must include at least six level flights over the measuring station at a height of 1,000 ±30 and ±10 degrees from the zenith when passing overhead.

(b) Each test over flight must be conducted—

(1) At not less than the highest power in the normal operating range provided in an Airplane Flight Manual, or in any combination of approved manual material, approved placard, or approved instrument markings; and

(2) At stabilized speed with propellers synchronized and with the airplane in cruise configuration, except that if the speed at the power setting prescribed in this paragraph would exceed the maximum speed authorized in level flight, accelerated flight is acceptable.

PART C—DATA CORRECTION

§ F36.201 Correction of data.

(a) Noise data obtained when the temperature is outside the range of 68 degrees F. ±9 degrees F., or the relative humidity is below 40 percent, must be corrected to 77 degrees F. and 70 percent relative humidity by a method approved by the FAA.

(b) The performance correction prescribed in paragraph (c) of this section must be used. It must be determined by the method described in this appendix, and must be added algebraically to the measured value. It is limited to 5 dB(A).

(c) The performance correction must be computed by using the following formula:

$$\Delta dB = 60 - 20 \log_{10} \left\{ \frac{(11{,}430 - D_{50})\ R/C}{V_y} + 50 \right\}$$

Where:

D_{50} = Takeoff distance to 50 feet at maximum certificated takeoff weight.

R/C = Certificated best rate of climb (fpm).

V_y = Speed for best rate of climb in the same units as rate of climb.

(d) When takeoff distance of 50′ is not listed as approved performance information, the figures of 2000′ for single-engine airplanes and 2700′ for multi-engine airplanes must be used.

§ F36.203 Validity of results.

(a) The test results must produce an average dB(A) and its 90 percent confidence limits, the noise level being the arithmetic average of the corrected acoustical measurements for all valid test runs over the measuring point.